A review of water-energy-food nexus frameworks, models, challenges and future opportunities to create an integrated, national security-based development index

Original
A review of water-energy-food nexus frameworks, models, challenges and future opportunities to create an integrated, national security-based development index / Yupanqui, C.; Dias, N.; Goodarzi, M. R.; Sharma, S.; Vagheei, H.; Mohtar, R.. - In: ENERGY NEXUS. - ISSN 2772-4271. - 18:(2025). [10.1016/j.nexus.2025.100409]

Publisher:
Elsevier

Published
DOI:10.1016/j.nexus.2025.100409

Energy Nexus 18 (2025) 100409

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

A review of water-energy-food nexus frameworks, models, challenges and future opportunities to create an integrated, national security-based development index

C. Yupanqui [a], N. Dias [a], M.R. Goodarzi [b,c], S. Sharma [a], H. Vagheei [d], Rabi Mohtar [a,e,f,*]

[a] Department of Biological and Agricultural Engineering, College Station, Texas A&M University, USA
[b] Department of Civil Engineering, Faulty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[c] Department of Civil Engineering, Yazd University, Yazd, Iran
[d] Department of Environment, Land, and Infrastructure Engineering, Politecnico di Torino, Turin, Italy
[e] Department of Civil and Environmental Engineering, College Station, Texas A&M University, USA
[f] Texas A&M Energy Institute, College Station, Texas A&M University, USA

ARTICLE INFO

Keywords:
WEF nexus
Sustainable development goals
Policy making
Framework
Model
Index
Security
Per-country

ABSTRACT

The Water-Energy-Food (WEF) Nexus has emerged as an innovative platform to assist with sustainable resource management. This review paper describes the WEF Nexus evolution during the last century and highlights its advances in tools, frameworks, and concepts. The paper critically assesses several aspects of the WEF Nexus including the milestones, major WEF frameworks, tools and models developed over the last twenty years, different WEF Nexus conceptualizations, and the significant support and investments reported in the 21st century. The relationship between the WEF Nexus and the Sustainable Development Goals (SDGs) is analyzed based on Nexus research studies, regional strategies or national programs were achieving WEF components lead to targeting some specific SDGs. The analysis of the principal WEF Nexus challenges and gaps emphasizes nature-driven crises such as water scarcity, energy shocks, and food shortages. Finally, the paper proposes a new business model that aims to quantify the water, energy, and food resources by country. The conceptual framework develops a WEF security index based on internationally recognized metrics and includes disaster risk and climate change, as well as trade-off as threats and contingency factors that are considered in the model. This review proposes a novel platform to assess the WEF security index per country as a pathway to contribute to SDGs 6,7,2,8 and 13.

1. Introduction

Water, energy, and food (WEF) are essential resources for human well-being and sustainable development. Water and energy are necessary for providing drinking and sanitation to cities, and for food production and the agri-food supply chain. Food production and its supply chains account for 30 % of the total energy consumed globally, and includes the energy required to pump water for irrigation and produce, transport, and distribute food [1].

Simultaneous to the complexity of the problem, there are fundamental facts on the unequal distribution of the WEF resources around the globe: (i) approximately one-tenth of the world's population faced global hunger between 2020 and 2021 (FAO, IFAD, UNICEF, WFP and [2]); (ii) nearly two billion people live in water-stressed countries with limited access to clean water [3]; (iii) in 2019, 10 % of the world's population were without electricity [4]; and (iv) 46 % of the world's population do not have access to safely managed sanitation facilities (improved facilities that are not shared with other households and in which excreta are safely disposed in situ or treated off-site) [5].

In future scenarios, WEF will face several challenges and threats from population growth, increasing energy consumption, and climate change [6–8]. Addressing WEF requires holistic thinking, an understanding of physical resource interconnections, socio-economic connections, and identification of "hotspots" to help us better grasp the challenges and formulate solutions that are grounded in science, socioeconomics, and human development. Since the adoption of the SDGs by the international community in 2020, many show limited or no progress. This raises concerns of not achieving them by 2030. The SDG Index estimates that 84 % of the targets have significant to major challenges and show either

---

* Corresponding author at: Department of Biological and Agricultural Engineering, College Station, Texas A&M University, USA.
E-mail address: mohtar@tamu.edu (R. Mohtar).

https://doi.org/10.1016/j.nexus.2025.100409
Received 8 August 2024; Received in revised form 7 February 2025; Accepted 16 March 2025

Nomenclature

ACCF	Africa climate change fund
ACCWAM	adaptation to climate change in the water sector in the MENA region program
AgWA	agricultural water for Africa
CIHEAM	international Centre for advanced Mediterranean agronomic studies
ECLAC	economic commission for Latin America and the Caribbean
ESCWA	economic and social commission for western Asia
FEW	food-energy-water
GEI	global energy institute
ICIMOD	international Centre for integrated mountain development
INFEWS	innovations at the nexus of food, energy, and water systems
JPI	joint programming initiative
MIFCP	multi-level interval fuzzy credibility-constrained programming
MuSIASEM	multi-scale integrated analysis of societal and ecosystem metabolism
MENA	Middle East and North Africa
NIFA	national institute for food and agriculture
NSF	national science foundation
PRIMA	partnership for research and innovation in the Mediterranean area
SDGs	sustainable development goals
SUGI-FWE Nexus	sustainable urbanization global initiative – food-water-energy Nexus
SWAT	soil and water assessment tool
UNECE	United Nations economic commission for Europe
UNDP	united nations development program
UNFCCC	united nations framework convention on climate change
UNU	united nations university
USDA	United States department of agriculture
WEAP	water evaluation and planning system

stagnation or decreasing progress. WEF related SDGs include: No poverty, Zero Hunger, Good Health and Well-being, Clean water and Sanitation, and Affordable Clean Energy [9]. In this sense, the use of WEF platforms at local, regional, or country level provides an opportunity to enter a new era of policymaking and resource management that aims for sustainable development, poverty eradication, and equitable distribution of resources and ultimately the achievement of the SDGs.

In general, Nexus review papers in academic journals aim to achieve the following common objectives: (a) synthesize the WEF Nexus literature, helping readers understand the current state of the art in Nexus studies; (b) identify gaps, challenges, and future research trends, particularly in areas lacking theories, methods, and research, to provide guidance for solving Nexus problems and conflicts [10]; (c) review and evaluate Nexus approaches and methods, assessing their strengths and weaknesses, and suggesting potential improvements [11]; (d) identify focus areas or facilitate integration across disciplines [12] to address existing gaps and challenges; (e) analyze existing frameworks to propose new model developments that enhance the understanding and application of the Nexus concept.

The objective of this review is to provide an insightful analysis of the following topics related to Nexus: (1) highlight the major milestones of the WEF Nexus development; (2) review and analyze the main WEF frameworks and models and to offer examples from different regions and thematic focus areas; (3) identify and describe study cases where WEF Nexus facilitates achieving the Sustainable Development Goals (SDGs); (4) identify Nexus gaps and challenges; (5) propose a descriptive novel approach as an international, comprehensive platform based on WEF security indexes, disaster risk, and climate change, and an indicator of trade-off and synergies that allow country assessment; and (6) case-application of the proposed approach in contributing with SDGs 6,7,2, 8 and 13.

This review emphasizes the benefit of implementing a country assessment platform that aims to inform progress in achieving WEF security by country toward the achievement of specific SDGs. The proposed model in this review is a novel approach that quantifies the WEF security index, estimates disaster risk and climate change as threatening factors to WEF resources, and includes a synergies and trade-off estimator as a contingency factor for resource security.

Finally, there is an imperative need to implement comprehensive country assessment approaches that monitor the achievement of WEF security and SDGs. Correspondingly, the novelty of this work, which differs from previous review studies, lies in its comprehensive and analytical manner of assessing major Nexus topics, ultimately creating an integrated, national security-based index.

2. Major milestones of the WEF Nexus

The United Nations (UN) recognizes the importance of the WEF Nexus for the future of humanity; member states introduced several goals to achieve sustainability including water, energy, and food-related objectives. Because achieving a target in one sector can impact targets in the other two sectors, the UN has recognized the need for a platform to assist policymakers in understanding the interactions among the goals for each sector. The WEF Nexus approach serves as a platform for assessing these interactions [11,13–20].

Various nexus-related conferences and workshops have taken place, and many projects and reports were developed. WEF Nexus stakeholders have become involved in Nexus activities. These include multinational institutions, corporations, institutes, Non-Governmental Organizations (NGOs), national and local governments and agencies, universities, private companies, and local businesses that work collaboratively toward sustainable development by quantifying WEF and then minimizing the trade-offs between WEF sectors, and risks of adverse cross-sectoral impacts [21–25,16,26–30].

Fig. 1 describes the timeline of the WEF Nexus and its evolution from its initiation in the mid-1980s to the most recent approaches and landmarks. Preview comments indicate that the first use of the Nexus term in the human environment was in 1983 [31–33]. The term was used in the book *Food and Energy – Strategies for Sustainable Development*, in which the authors acknowledge the Food-Energy Nexus Program of the United Nations University (UNU) [34]. A year earlier, the project proposal on food-energy nexus submitted to the UNU aimed to serve as the initial point for local solutions to global problems and efficient use of resources [35]. Subsequently, two international conferences in this field took place: the first, “Food, Energy and Ecosystems” was held in Brasilia and organized by UNU; the second, “Second International Symposium on The Food–Energy Nexus and Ecosystems” took place in New Delhi and was organized in by UNU [31].

In the late 1990s to 2000, Columbia University’s Earth Institute studied India’s water, energy, and agriculture nexus. Subsequently, Scott [36] addressed the electricity-water nexus in Mexico. In 2011, the WEF Nexus was described as a global risk [37]. A landmark report launched by the World Economic Forum in 2011, alerted the world’s political and business leaders of the need to examine the interconnections between global challenges related to WEF resources, climate, economic growth, and human security

Endo et al., [16]. In 2013, the Government of Qatar hosted the Doha Climate Change Conference, introducing the Nexus at climate talks [38]. To promote interdisciplinary research, Future Earth was introduced as a

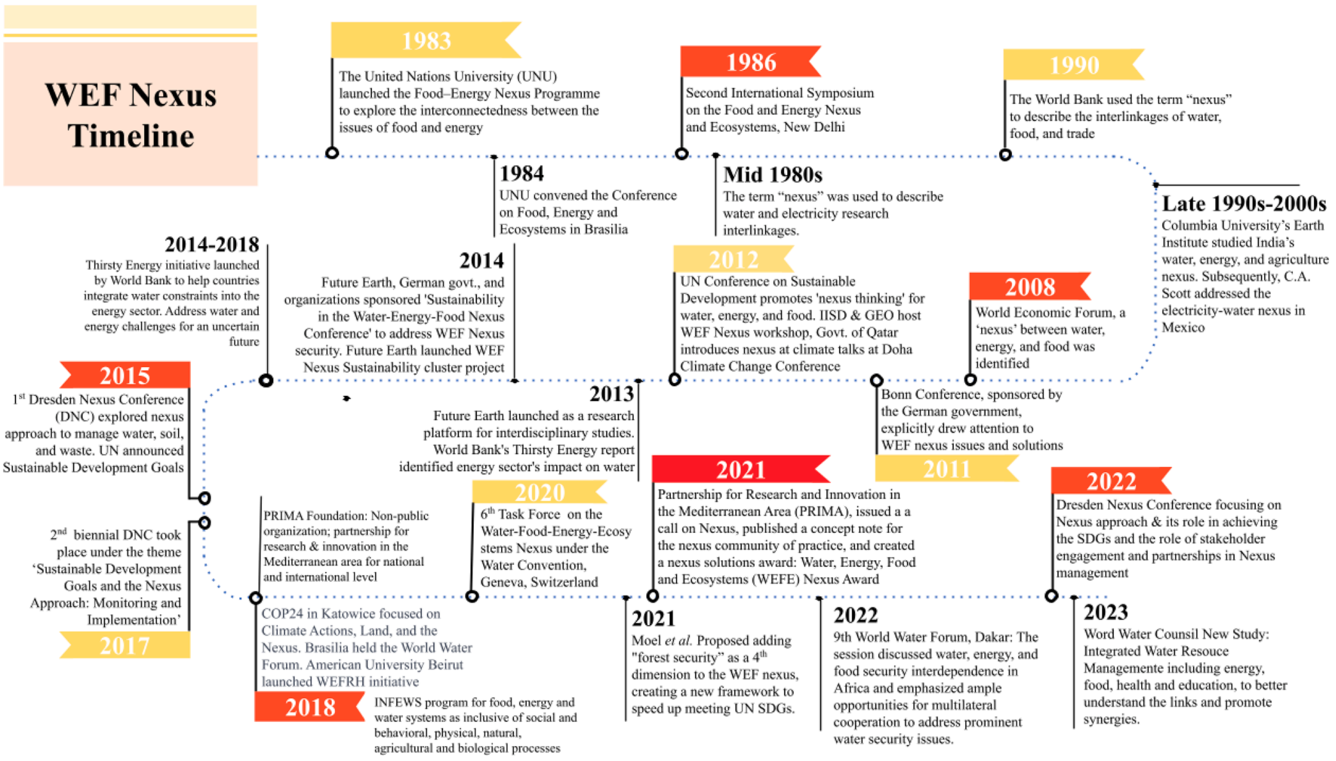

Fig. 1. The WEF nexus timeline.

global research platform ([16]a). After identifying the WEF Nexus as a Global Risk at the 2011 World Economic Forum, scientists and decision-makers increasingly recognized the need to understand the WEF Nexus and its complex interrelationships that produce, deliver, and utilize goods and resources [39]. Bazilian et al. [21] indicated the need for systems thinking to address the challenges and potentials of energy, water, and food policies. While problems differ with regions, Lawford et al. [40] concluded that the WEF Nexus approach can provide a framework for advancing water and sustainability issues in all regions.

In November 2015, Texas A&M University organized the Resource Nexus Water Forum to highlight the necessity of a global effort to bridge the gap between water demand and water availability [41]. Similarly, the Brasilia World Water Forum (2018) included a stakeholder forum on the WEF Nexus and SDG implementation. In 2018, the Dresden Nexus Conferences and the EGU General Assemblies, among others, focused on the SDGs and the Nexus approach and its application to achieve the SDGs. At their triennial Word Water Congress (2017), the International Water Resources Association (IWRA) adopted Nexus as a systems platform for addressing future water challenges. Since 2014, the World Water Council established the transversality water management task force to expand the integrated water resources management concept by including the nexus of water, energy, food, health, and education. PRIMA, the EU funding agency for the Mediterranean region, launched a call on the Nexus including a concept note on establishing the nexus community of practice and an award for the nexus solutions. Melo et al. [42] suggested adding 'forest security' as the fourth dimension of the WEF Nexus and developing a new framework to accelerate meeting the UN SDGs.

3. WEF Nexus frameworks and tools

In WEF Nexus parlance, a framework attempts to offer a discourse on global challenges: not only to provide fresh water and energy when needed but also to achieve food security [43]. WEF qualitative and quantitative tools generally aim to bring about a structured knowledgebase for sustainable socio-economic development. Specifically, the tools and framework investigate scenarios to identify and assess management strategies that can be useful to decision-makers. Additionally, WEF models tend to develop computer simulations to derive the relationship between water, energy, and food [44]. An overview of WEF frameworks, tools, and models follows.

3.1. WEF frameworks

Policy making requires mechanisms that incorporate water, energy, and food interlinkages to achieve WEF security by providing holistic and integrative management strategies to plan future allocation of these vital resources [45]. The WEF Nexus approach serves as a platform for assessing the interactions. As is obvious from the many WEF Nexus frameworks described, they vary in scope, goal, and significance of drivers and pressures. WEF platforms provide an opportunity to enter a new policy-making era with resource management that allows sustainable development, poverty eradication, and equitable resource distribution using the WEF approach.

From a WEF security perspective, the World Economic Forum [30] used a Nexus framework to introduce the links between resources and provide the essential rights to water, energy, and food security. The World Economic Forum [37] rightly placed equal emphasis on each system: water, energy, and food. Subsequent studies considered various facets and alternative components [46,43].

Hoff [27] places water resource availability at the center of the nexus framework, in which water supply, energy, and food security are the three nexus pillars. Water is a non-substitutable resource in biomass production, acting simultaneously as a state variable and a control variable of change. Society is the "action field" since water, energy, and food security are crucial for potential development (improving livelihood conditions for the "bottom million").Ringler et al. [47] consider food as the core component of water, energy, and land linkages. Liu [48] developed a conceptual framework that includes major climate change drivers interlinked with life cycles in water, energy, food, and related biosphere and ecosystem processes. ICIMOD [49] focused on the Himalayas and South Asia, where ecosystems are key, and represented a connected triangle of WEF with agriculture at its core [50].

Mohtar and Daher [45] introduced an integrated WEF Nexus framework for inclusive dialogues catalyzed by science and including three major elements: a) the WEF Nexus analytics platform involving interlinkages and trade-offs for managing hot spots; b) the supply chain and political economy dialogues representing the private sector, business, industries, government and society; and c) the cooperation and conflict as the links between the mentioned dialogues as means to addressing problems between the two key players. This WEF nexus analytic platform provides a level-playing field approach to inclusive dialogue for problem-solving.

Al-Saidi & Elagib [51] introduced the concept of issue integration within the WEF nexus. This framework integrates the management perspective of the three resources by analyzing the state of their integration. It attempts to quantify the interactions between these resources. The approach involves three key understandings: integration as incorporation, referring to the combination of the three sectors into one system where all parts are equally important; integration as cross-linking, which focuses on concrete interconnections and priority issues; and integration as assimilation, referring to how strategies from key sectors are incorporated into the operational management and decision-making processes of other sector strategies.

Recently, Simpson et al. [52] developed a WEF Nexus Index as a country-level index calculated for 181 nations using open databases. The index was built according to the European Commission JRC Competence Centre methods on Composite Indicators and Scoreboards.

This review highlights how the multi-centric approach enhances the Nexus framework, with water, energy, and food as its principal components, complemented by other resources. Incorporating elements such as soil, environment, land or ecosystem, society, and economy adds value and purpose to its application across various cases, regions, and scales. However, this diversity in framework approaches can also be seen as a limitation when attempting to define the state of the art in Nexus research [19].

3.2. *WEF tools and models*

To support the development of effective, integrative resource allocation strategies, policymakers require comprehensive tools and models with a variety of analytical approaches that can define and quantify the interlinkages of water, energy, land, and food resources. The tools should enable them to estimate resource requirements and consider various future scenarios for identifying trade-offs between nexus components [53–56].

The aim of this section is to develop a critical analysis of the reviewed Nexus tools. As an example, a list of Nexus tools is included in Table 1, where various water, soil, and crop (food) management tools are distinguished and compared with other, more specific Nexus tools. In agreement with the work of Taguta et al. [57], which analyzed 46 Nexus tools from the literature, these tools share certain functional characteristics: a) Availability to users: free access is not always guaranteed due to the complexity of certain tools, although most Nexus tools are intended to be free to use; b) Format type: Nexus tools vary in format, ranging from open-access web tools, Excel sheets, software, or GitHub platforms; c) Flexibility of application scope: This refers to the geographic setup of the tool, such as local, regional, or country-based. Nexus tools are often designed for a specific scope and geographic area, while some provide the flexibility to shift among these scopes, offering more versatility to users.

On the other side, Nexus tools show some intrinsic characteristics such as:

(a) Resource integration: Nexus tools typically integrate the management of water, energy, and food resources. Some tools provide integration and interlinkages applied at various geographic scales. For instance, the Water, Energy, Food Nexus Tool 2.0 is applied in Qatar, while the WEF Nexus Index from Simpson et al. [52] is applied on a country-level basis. However, other tools focus on detailed analyses of one or two resources (e.g., water or energy) and their integration with crops (food), land, greenhouse gases, climate change, and others, often omitting one or two resources from the analysis. Examples of these tools include EPCI, SWAT, DSSAT, CropSyst, WEAP, and MARKAL. To avoid undermining the Nexus objective, these tools should be coupled with analyses of the omitted resources to achieve comprehensive three-resource integration and interlinkages.
(b) Trade-off analysis: This is not always included in Nexus tools as it typically analyzes specific resource alternatives for a given case. However, trade-off analysis enriches the Nexus approach by addressing "what-if" scenarios regarding alternative resource allocation. Tools with trade-off analysis add value by providing insights into resource interdependencies and allocation challenges.
(c) Sensitivity analysis: Sensitivity analysis is often omitted from Nexus tools, yet it provides valuable information for modeling uncertain resource scenarios. For example, the DSSAT model includes this feature. Sensitivity analysis allows the variation of resource quantities around other resource values to explore how small changes could influence the final Nexus performance outputs [70].
(d) Inclusion of societal and economic impacts: Tools such as ANEMI, MARKAL, DSSAT, and MuSIASEM address socio-economic impacts within Nexus models. These models include features that measures societal and economic impacts being particularly valuable for decision-making process to governmental entities.
(e) Decision support systems: Most Nexus tools aim to support decision-making for governmental entities across various sectors by assessing current performance and projecting future scenarios. Examples include the Q-Nexus Model, the WEF Nexus Index, the Nexus Tool 2.0, and ANEMI (see Table 1).
(f) Open-source data inputs: The availability of data can pose challenges when using Nexus tools. Tools that provide open-source data pre-arranged are particularly preferred.

4. WEF Nexus conceptualization

This section aims to approximate an overall WEF Nexus conceptualization. Its definition from the academic literature is a broad, complex approach that includes several terminologies [71]. Based on the analysis of 304 papers in the proposal of Fernandez Torres et al. [72], the Nexus definition goes from a non-standard approach to integrating and managing WEF sectors by inter-coordination to reach sustainable development. Their Nexus concept is named the multisectoral management tool that characterizes and evaluates qualitative and quantitative interrelated and interdependent systems. Some key features in the Nexus concept analysis included the multifaceted networked systems since Nexus depends on interconnections and multiple interactions among different sectors.

Nexus is defined as the integrated management paradigm, as explained in the work of Al-Saidi & Elagib [51], who argued that the Nexus holistic view shifts its focus to cross-sectoral issues and considers the analysis of concepts, postulates, and methods under three aspects: (a) intersectorality of resource use issues, (b) interdependence and interdisciplinarity of management decisions, and (c) interactionality of impacts of resources allocations. Moreover, they recommend observing the interdependent resource issues of water, energy, and food using an integrated framework grounded in scientific analysis.

A definition given by Mohtar [73] provides three principles that holistically conceptualize the Nexus approach. First, water, energy, and food management should maintain an integrative view at all levels focusing on the inclusiveness for all sectors: governance, academic, civil society, and private. The second principle establishes the

Table 1
Description of nexus tools.

Tool/Method	Analysis type	Scale/ Geographic level	Type of software	Purpose	Limitations	Applications examples	Author(s) / Organization	Refs.
EPIC (Environmental Policy Integrated Climate (originally known as erosion productivity impact calculator)	Simulation model	Regional National Global	Web-based, open source	To study impact of soil erosion on its productivity	Model doesn't work accurately with limited data	To assess nitrogen and phosphorus losses from fertilizer and manure applications through surface runoff and leaching	FAO	[58]
The Water, Energy, Food Nexus Tool 2.0	Simulation model	National	Web-based open source	Provides a standard platform for evaluating scenarios and identifying sustainable national resource allocation plans for scientists and policymakers.	Limited to national scale utilization	Study of sustainable food self-sufficiency possibilities for Qatar	Mohtar and Dahler	[59]
SWAT, the Soil and Water Assessment Tool	Simulation model	River basin scale	Open-source access	To forecast the effects of land management techniques on water, sediment, and agricultural chemical outputs across a large complex watershed with shifting soil, land use, and management conditions over extended periods of time	Requirement of lots of data makes calibration tiresome	Evaluate crop yield and amount of water flowing	USDA	[60]
MuSIASEM, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism	Simulation model	Regional National Global	Open-source access	Characterizing the metabolic patterns of socio-ecological systems	Requires lot of information which is not readily available	In developing nations, MuSIASEM accounting has been used for the comprehensive evaluation of agricultural systems, biofuels, nuclear power, energetics, water usage sustainability, mining, urban waste management systems, and urban metabolism.	Mario Giampoetro and Kozo Mayumi	[61]
DSSAT	Simulation model	Global	Open-source access	By integrating the influences of soil, crop genotype, weather, and management options, DSSAT enables users to pose "what if" questions by quickly running simulated experiments.	Model doesn't respond to all environmental management factors.	Examination the effects of irrigation management methods for long-term (30 years or more) weather conditions.	US Agency for International Development (USAID)	[62]
MARKAL (Market Allocation)	Simulation model	Global	Open-source access	Enables analysis of the mid to long term technological decisions that influence how an energy system evolves to achieve environmental or other goals. The model enables comparison and analysis of the effects of various regional policy approaches.	Not suitable for immediate planning or emergency response. Requires several data inputs.		International Energy Agency	[63]

(continued on next page)

Table 1 (*continued*)

Tool/Method	Analysis type	Scale/ Geographic level	Type of software	Purpose	Limitations	Applications examples	Author(s) / Organization	Refs.
SWAP model (Soil Water Atmosphere Plant)	Simulation model	Field level scale	Open-source access	SWAP mimics the movement of heat, solutes, and water in the vadose zone in relation to the growth of plants.	Other transport models, such as PEARL and ANIMO, are advised for comprehensive pesticide and nutrient flow combinations.	Using past and projected climatic data, an examination of the effects of drought, water surplus, and salinity on grass productivity in The Netherlands	The Water Resources Group of Wageningen University	[64]
CropSyst (Cropping System Simulation Model)	Simulation model	Field level scale	Open-source access	to investigate the effect of crop management practices on productivity	Has a few issues, especially when applying to conditions that the model does not mimic (for example, water balance of cracking vertisols).	Identification of significant evaporation losses from the winter wheat (WW) and summer maize (SM) rotations by simulating real evapotranspiration (ETa), biomass, and grain production.	Claudio Stöckle (Project Leader), Roger Nelson, and Armen Kemanian	[65], ([66]
ANEMI	An integrated assessment model	Global	Open-source access	To evaluate global change-related policy scenarios that emphasize the importance of water resources	The ANEMI model's globally aggregated structure has the unintended consequence of making it unable to depict processes with finer temporal scales, such as climate influences on flooding and heatwave events, even with a finer time step.	Integrated System Dynamics Model for Studying the Social, Energy, Economic, and Climate System	Evan Davies and Mohammad Akhtar	[67]
WEAP	Simulation model	–	Open-source GIS Tool	It offers a mechanism for maintaining data on water supply and demand.	Functionality is relatively weak; Inability to iterate through several time steps or within a time step. - No capability for multi-period optimization. - Absence of rule-based simulation capability.	To model water demand, supply, runoff, storage, streamflow and pollutant generation and dispersion, as well as the quality of instream water	Stockholm Environment Institute's U.S. Center	[68]
Q-Nexus Model	Quantification and simulation functions/ Model	Local, regional National and global	Open source	A quantitative assessment that analyzes intersectoral quantitative usage and resources demands	The scenario evaluation of increase demand or consumption does not account for resource constraints: such as water and energy limitation.	The methodology was applied to evaluate the water, energy and food nexus in Lebanon for 2012	Ali Karnib, Lebanese University, Hadath Campus, Baabda, Lebanon	(Ali [69])
Water-Energy-Food (WEF) Nexus Index	National-level composite indicator model	Country level	Opens source	Application of a country-level index, calculated in 181 countries using open databases	The application offers ranking of countries but does not account for tradeoff analysis.	The WEF Nexus Index was implemented in a world map on selected countries	Water Research Commission and the National Research Foundation both of South Africa, and the Ministry of Foreign Affairs of The Netherlands.	[52]

interconnectivity among the WEF resources, which must be the core when creating policy and planning. Third is the strategic role of the private sector in supply chain management, mobilization and resource conservation, responsible investment, and research and development for enhancing business opportunities and technology development.

An earlier definition of Nexus brings up the term security in water, energy, and food management, which are linked to the system's demands on water and energy when managing the system and its effect on food prices. In addition, environmental and climatic changes, and economy and population growth are the factors that intensify the relations between the three resource-systems. From this scenario background, the Bonn Conference [74] identified Nexus as the new approach to address levels of insecurity in access to essential services, which better acknowledges the inter-linkages and inter-dependencies across the three sectors and the influence of trade, investment, and climate policies [75].

Finally, Mohtar [73] directly framed the Nexus definition with the platform of a system of systems that connects the WEF subsystems and whose internal elements include interlinkages, hotspots, and tradeoffs. It is based on three elements: water productivity, energy efficiency, integrated water resources management for food, energy, and water, respectively, and connects government policy, society, and business supply chains in a trinomial loop.

Another terminology in Nexus's conceptualization is water––energy–food–ecosystems (WEFE) Nexus, which integrates management and governance across the four sectors and is characterized by its complexity and interconnectedness between water, energy, food, and ecosystems (UNESCO, [76]). The inclusion of the ecosystem in Nexus responds to the connection between healthy ecosystems and natural resources, where mutual interconnection and interdependency are the basis to support ecosystem services to ensure water, food, and energy security. Indeed, any limitation in water resources inputs disturbing the quantity or quality prevents the access of the others and consequently breaks a good Nexus balance.

5. WEF Nexus support and investment

The WEF Nexus implementation requires investment, new ways of thinking, and flexible forms of governance to achieve effective, sustainable solutions to nexus-related challenges [77,78]. At some WEF gatherings, water was introduced as a highly strategic asset with economic potential and serious implications for the security of nations and businesses. The WEF Nexus concept is supported by several multinational corporations, including Nestle, PepsiCo, and Unilever, who hosted meetings on water security from 2005 onward [79].

In 2009, during the Davos World Economic Forum, private sector interest in water security was highlighted. Nestle chairman Brabeck-Letmathe signaled his concern about water quality and scarcity, noting: "I am convinced the world will run out of water before running out of fuel" [80]. The 2030 Water Resources Group and the global consulting firm McKinsey effectively launched 'Charting Our Water Future' funded by the private-sector and bringing water security to the attention of a wider group of corporate decision-makers [81]. Since then, WEF Nexus meetings and activities have received both corporate and public-sector support. Although changes in public sector financing and corporate practices are not significant, the Nexus concept continues to grow around the world, attracting donors and stakeholders including national and regional governments, international aid agencies and environmental NGOs [82,79].

The Ouarzazate Concentrated Solar Power Plant project in Morocco was funded through a World Bank loan [83]. There seems to be increasing global political willingness to integrate renewable energy capabilities: the Paris Climate Agreement demonstrates this willingness and created financial aid opportunities for developing countries. The UNFCCC Adaptation Fund Renewable supports energy projects in developing countries, where industrialized nations committed to support less affluent countries by mobilizing US$100 billion annually by 2020 (UNFCCC—COP16, Cancun). The new Green Climate Fund of the UN raised US$10 billion (with a target to increase to US$100 billion by 2020) to support poor nations as they address climate change. The Africa Climate Change Fund (ACCF) allocates small grants to support developing economies in transition to low carbon development [84]. Energy innovation that leads to producing clean energy is an effective way to enhance energy security: it improves the environment and protects public health and natural resources. Many countries invest in these opportunities. In the U.S., many innovative products were successfully commercialized by Tesla, General Electric, and First Solar. Eleven countries invested more in energy R&D than the U.S.: most notably China, which spends three times as much as the U.S., [85] on this research.

In 2012, PRIMA Foundation was stablished as a non-profit organization for public service responsible to implement PRIMA Programs, projects and awards. Among them, PRIMA WEFE Nexus award distinguishes outstanding teams of researchers and practitioners that have used their outcomes to demonstrate the socio-economic benefits of their proposed practices through a WEFE Nexus approach in the Mediterranean region. The Prize recognizes "research teams and practitioners" that have devised and demonstrated the successful implementation on the ground of combined management practices of water, energy, food and ecosystem resources in the Mediterranean, at local, sub-regional, and or regional levels.

In 2016, the U.S. government invested about $6.4 billion on clean energy R&D across a dozen agencies (Fig. 2). After funding a series of interdisciplinary FEW workshops, the National Science Foundation (NSF) released its first call for Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) in December 2015 [86].

In September 2016, NSF, announced investments of more than $72 million for their INFEWS program to help secure the future of the WEF Nexus systems while maintaining vital ecosystem services. NSF partners with the USDA's National Institute for Food and Agriculture (NIFA) through the joint NSF-NIFA program on INFEWS to achieve these goals, (see <https://nifa.usda.gov/innovations-nexus-food-energy-and-water-systems-infews>).

Global efforts to bring together fragmented research expertise and find innovative new solutions to the WEF Nexus challenge include the Belmont Forum, a group funding agency from different nations, and the Joint Programming Initiative (JPI). Urban Europe developed the Sustainable Urbanization Global Initiative – Food-Energy-Water Nexus (SUGI-FEW Nexus), supported by the European Commission through Horizon 2020 and with an available budget of 28.5 M€ (SUGI-FWE [87]). An important aspect in investment and financial support remains the integration and scalability of the Nexus and the possibility of developing successful business cases that can be replicated across countries globally.

6. The WEF nexus and SDGs

Water, energy, and food are essential resources for human beings and play a critical role in sustainable development. Rapidly growing global population is increasing the demand for these resources and emerging challenges, such as climate change, are further increasing the pressure on them. According to the predictions of global population growth, in 2030 the demand for energy, food, and water will be increased by 50 %, 35 %, and 40 % (respectively) over 2010 [88]. Water, energy, and food resources are unevenly distributed around the world and in September 2015, a list of 17 SDGs was announced by the UN General Assembly to be accomplished by 2030 to ensure the rational use of these limited resources to achieve global sustainability and security. These 17 SDGs are operationalized through 169 targets and 232 specific indicators and include diverse dimensions of social, economic, and environment. 193 member nations of the UN committed to integrate these goals for formulating and implementation of national policies and making global partnerships to achieve the SDGs [89].

The WEF Nexus approach describes the importance of interrelationships between systems rather than an isolated system. Among 17 SDGs, the SDG 2 (Zero hunger), the SDG 6 (Clean water and sanitation), and the SDG 7 (Affordable, clean energy) are mainly targeted to achieve global food, water, and energy security. Certain other SDGs are also directly or indirectly related with one or more components in the WEF Nexus approach while creating synergies between different sectors. Achieving one target of SDGs will have direct and indirect impact on other SDGs [13]. Though adoption of the WEF Nexus approach reduces risk that the actions initiated in favor of SDGs weaken each other, it is considered the pathway to achieve SDGs by integrated management and governance of different sectors and scales [90]. A recent study on water-energy-food sustainable development goals in Morocco clearly shows the way to apply WEF Nexus tools to achieve the SDGs in local scale [13]. Some of the regional strategies and programs initiated to achieve water, energy, and food security are presented below.

With population and economic growth, many eastern and southern Mediterranean countries are expected to experience significant increases in energy demand as those countries are heavily dependent on fossil fuels. The Food and Agriculture Organization (FAO) Energy-Smart

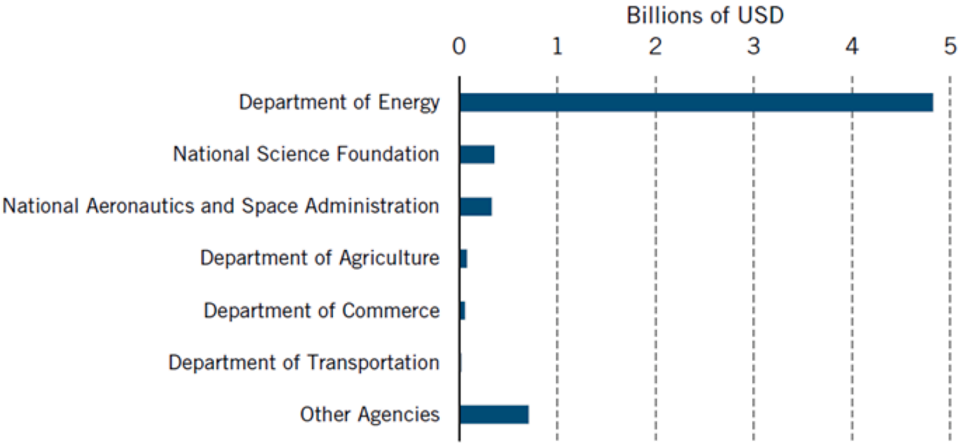

Fig. 2. Federal funding from U.S government for clean energy R&D in fiscal year 2016 [85].

Food for People and Climate Conference discussed this challenge [91] and reported that energy efficiency improvements and use of renewable energy can raise sustainability, decrease agriculture dependence on fossil fuels, and reduce agricultural greenhouse gas emissions. However, it will be necessary to have financial support, better gender balance, support for producer organizations, standards, guaranteed markets, improvements in policy, and institutional measures. The FAO Nexus approach seeks to promote dialogue between water, energy, and food in southern and eastern Mediterranean countries. The International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM) places significant focus on energy issues in its post-2015 Agenda, particularly implementation of MED-SPRING due to increasing overlap of the water-climate-energy Nexus and the strong links between agriculture and energy consumption [91].

Food security crises, such as the Greater Horn of Africa famine in 2011–2012 that affected 13 million people, primarily in southern Ethiopia, south-central Somalia, and northern Kenya, refocused the world’s attention on food, agriculture, and rural development, helping to re-establish food security as a global priority. As a result of humanitarian and development investments made by communities and governments in the Horn of Africa, vulnerability has lessened, and disaster management capacity has increased. Today, as farmers struggle to sustainably harness the productive potential of semi-arid lands to mitigate repeated crises, the regional, national, and continental leaders in Africa together with global leaders from the development community are introducing sustainable water management initiatives. FAO and AgWA (the Agriculture Water in Africa) implemented a project to support agricultural water management in Kenya, South Sudan, and Uganda [92]. The government of Ethiopia established the Growth and Transformation Plan (2010) and the Climate-Resilient Green Economy strategy (2012) to sustainably develop and modernize the national economy in a climate-compatible fashion using a variety of targets related to the agriculture and energy sectors [93]. Recognizing that water resources are critical to food and energy security, Indonesia set about improving the water supply as a primary development goal, addressing challenges such as climate change, water storage capacity, groundwater depletion, and watershed degradation. Maintaining energy supply and achieving universal access to electricity are targets for Indonesia’s National Medium-Term Development Plan [94].

Regional strategies relevant to WEF security for improving capacity of United Nations Economic and Social Commission for Western Asia (ESCWA) member countries to achieve the SDGs [95] include Arab strategy for water Security in Arab Region to meet the challenges and future need for sustainable development (2010–2030), strategy for sustainable Arab agriculture development for upcoming two decades (2005–2025), PAN-Arab strategy for the development of renewable energy applications (2010–2030), Arab initiative on the WEF Nexus, building capacity on the Food-Water nexus in ESCWA region, adaptation to climate change in the water sector in MENA region program (ACCWAM), Arab framework Action plan on climate change, and Arab strategic framework for sustainable development.

South America is adopting WEF Nexus approaches to encourage increased investment in key services. Specifically, the Nexus Regional Dialogue in Latin America works in close cooperation with the United Nations Economic Commission for Latin America and the Caribbean (ECLAC) to support research, recommend policies changes to strengthen management of natural resources, and engage other national, regional, and international institutions, governments, and relevant stakeholders to ensure more investment and endorsement of the WEF Nexus.

Different relationships between the WEF Nexus approach and SDGs were studied at local, regional, and global level in recent years. These studies mainly addressed relationships among one or more components in WEF Nexus approach with various environmental, economic, and social aspects included in SDGs and their targets. For instance, the EU-funded CWASI (Coping with water scarcity in a globalized world) project coordinated by Politecnico di Torino (Italy) addresses food and water security by merging ideas, concepts, theories, and methodologies from Hydrology, Sustainable Development, Economics, Complexity Theory, Climate Change, and Nutritional Sciences, Geopolitics and Agronomics, and Renewable Energy ([96]; https://www.watertofood.org/).

Food production systems are the core of the SDGs and most WEF Nexus research focuses on understanding and optimizing water and energy use to improve efficiency in food production systems on a small scale to regional level. These include assessing the sustainability of farming systems, sustainability of different management practices, optimization of irrigation and nutrient management in crop production [97,98,90,99]. Soil is the most important component in the food production system and has significant impact on water, food, and energy security, but is not studied as relates to the WEF Nexus approach [100,101].

Climate change is one of the critical global challenges that have many implications on food water, and energy security and sustainable development. It gained more attention in formulating SDGs and was included as SDG 13- climate action. Many other SDGs included targets that address solutions to combat climate changes and its impacts. Assessment of the WEF Nexus with the sources and impacts of climate change provides more insights to initiate policy decisions to mitigate the impacts of climate change. Recent studies such as WEF-climate change, WEF-GreenHouse Gas emissions, and WEF-land use changes are providing more understanding on interconnections between WEF and climate change on regional and global level [102,103].

The Nexus of WEF-waste, WEF-environment pollution, WEF-ecosystems, WEF-biodiversity and WEF-health [104] are another emerging area of research which is linked with SDGs such as sustainable cities and commodities (SDG 9), responsible consumption and production (SDG 12), life below water (SDG 14), and life on land (SDG 15) [88,105,106]. Integration of the WEF Nexus approach on resilience analysis, life cycle assessment, environmental footprint analysis, and integrated resource management such as integrated water management are also gained more interest in regarding to sustainable development [107–109]. Recent studies on applications of the WEF Nexus with supply chain management have gained attention and provide thorough understanding of entire production systems and have significant impact on efficient use of resources and sustainability [110].

The Water-Employment-Migration (WEM) framework, introduced by GWP-Med in 2016, focuses on increasing employability and entrepreneurship by addressing water-related issues in countries of origin, transit, and host nations. It promotes sustainable water management, gender equality, and youth participation. A case study presented by Hussein & Ezbakhe [111] highlights how to operationalize the WEM nexus at the policy level to tackle unemployment and water security in the MENA region. However, no concrete examples were provided. A possible implementation of the WEM nexus at the local or regional level could involve the development and execution of integrated water resource projects that encompass sanitation, agriculture, and energy sectors. Such interventions stimulate the local/region economy and create employment opportunities in the region. Indeed, the WEM framework become a valuable tool for monitoring the progress in water security (SDG 6), decent work creation (SDG 8), and economic growth (SDG 8) in the region.

Combination of the WEF Nexus with Circular Economy (CE) concept is gaining attention among researchers to achieve the SDGs [109]. The CE concept is based on reuse and recycling of products and materials to save water, energy, and other resources while ensuring the balance between supply and demand from different sectors in a closed system [112]. The CE concept links to many of the SDGs: linking the WEF Nexus approach to the CE concept will have more benefits towards achieving SDGs.

The progress of achieving SDGs has real challenges for both developed and developing countries. Most countries have not achieved the planned progress towards SDGs, especially due to the COVID-19 pandemic. Both developed and developing countries can accelerate the progress of SDGs through Nexus thinking. Findings of the WEF Nexus studies also highlight the need for more research and case studies to combine WEF nexus with SDGs. Comprehensive and quantitative analysis of different sectors can efficiently contribute to developing policies and frameworks at regional and global level to achieve the SDGs.

7. WEF Nexus challenges and gaps

Water, energy, and food system resources face real challenges due to rapid population growth, climate change, and economic recession that prevents investment in improved energy and water resources infrastructure. Food crises, water scarcity, and energy shocks are highlighted among the top risks to the modern world by the Global Risk reports from 2007 through 2019 [113]. By 2035, water consumed in generating energy is expected to rise by about 85 % due to the projected increase in energy demand (35 %). Food production requires more land, water, and energy; it carries an increased risk due to the potential trade-offs related to expanded use of bioenergy [61,114]. The changing climate will increase pressures on water, energy, and food resources and potential resource reduction will leave millions of people without WEF security. In general, communities have little or no resilience to seasonal rainfall anomalies due to changing climate: it seems necessary that various sectors, including private, public, and civil society, work together to develop innovative approaches for mitigating impacts on these vital resources [114–116,84].

The interlinkages between the WEF systems for meeting the growing demand for resources represent a significant challenge at the regional level, and the management of one sector can no longer be in isolation: it must be addressed as part of an integrated system [117,118]. These interlinkages and interdependencies face the challenge of simplicity versus complexity of implementation and addressing trade-offs [28,118,19,56].

At regional or country scales, governance of the WEF nexus represents a challenge when implementing a multi-actor role with a wide range of involved stakeholders, including private and public systems that manage the supply and demand of water, energy, and food [119,78,120,121,19]. This role implies the effective, innovative planification and execution that ensure synergy between resources is achieved and interdependencies reduced [122–126].

Another challenge is data gaps, including access to data, lack of interlinkages data, incompatibility of available data with the nexus tools requirements, lack of compatible data across scales, and lack of sufficient knowledge to work with nexus tools [127]. Other gaps in the WEF Nexus to cope with these challenges constitute the lack of an international consensus on its principal metrics and components. The definition of a suitable unit of analysis that enables analytical comparison in a global approach is not fully defined in the Nexus knowledge. These gaps restrain the process of measuring the performance and comparison from an international perspective, which brings up the importance of developing indexes by countries and comparative metrics with an analytical platform and a set of criteria.

Governance remains a challenge when nexus is implemented across sectors at different geographical scales. Stein and Jaspersen [128] explained the governance definition in Nexus as the relational structures and processes implemented among actors across sectors, and different governance levels, geographical boundaries, and/or public, including private and civic groups. In practice, this process implies a set coordination of actions, involvement, and decision-making across sectors and actors, and remains a challenge when policies lack integral connection and work as a silo-oriented set of rules. Aside from the Nexus governance theoretical approach, the lack of frameworks and tools that facilitate the ‘grounding’ process of the nexus governance in local realities is a major gap [128,129], leaving the ‘nexus concept disconnected from the decision-making and policy-making processes influence’ [128,130].

Therefore, addressing WEF resource challenges requires holistic thinking and an understanding of physical resource interconnections, socio-economic connections, and the emergence of “hotspots” to help us better grasp the challenges and develop solutions to them. Mohtar & Daher [45] noted that policy and decision-makers need comprehensive tools that: (i) define and quantify the interconnectivity between water, energy, and food resources; (ii) bring information resources to elaborate integrative and holistic management strategies for future allocation planning; (iii) are inclusive of all stakeholders for a multi-scale application from local to regional and national. Adding to the cited needs, a final global consensus on metrics and components will benefit to grasp country indexes and comparison across nations to address WEF Nexus towards an international platform.

8. Need for a security-based systems approach for national sustainable development

Achieving water, energy, and food security requires feasible implementation mechanisms for each sector and synergies among sectors. Addressing these complex challenges and resource interlinkages requires the adoption of a new integrated paradigm for resource allocations with holistic solutions and interventions [118,131].

A new approach is defined as a system of systems that comes with a large set of mathematical formalities that analyze the systems rigorously and offers a considerable toolkit of techniques created to assess WEF Nexus problems and risks [45,84]. A systemic approach includes the study of the system’s integrated assessment, simulation, and modeling, based on historical data and formulating projections. The objectives of the new model focus on finding the driving forces that jeopardize the

WEF system, by looking at the lack of resources and synergies, and understanding the interdependencies, vulnerabilities, and inequalities of the resource distributions. Such an approach enables knowledge-based dialogue that identifies goals for moving beyond sectoral efficiencies toward sustainable resource systems. It also enables policy makers to understand the trade-offs between and the intersections of the Nexus elements.

Achieving water – energy – food security is considered a necessity for many countries. Indeed, it is part of human security as it entails the well-being of individuals to respond for people's needs in dealing with sources of threats [95]. Any created Nexus system model should address the dependency on the availability of water, food, and energy resources in the most optimal and strategic manner. Addressing water–energy–food from the security approach in the development of a new system platform is well supported.

Al-Saidi and Hussein [132] proposed the need for security-based assessments within the WEF nexus, incorporating risk- and shock-related aspects for both the short and long term, with a focus on integrated resource-supply systems. For example, the analysis of COVID-19′s impacts revealed negative effects on the food, water, and energy sectors, which were transmitted at different rates due to the temporal dynamics of resource-supply security within the WEF nexus [133].

The proposed new system should aim to integrate into an international platform that allows country assessment and comparison to cope with the lack of global WEF consensus. A global, security perspective is needed to bring an international base and comprehensive, uniform platform, given the diverse and complex interpretations of the food, water, and energy security metrics. The approach should address and characterize the system by building future scenarios utilizing mathematical tools that allow maximizing the Nexus system components, minimizing disaster risk and climate change, and estimating a proxy value for trade-offs and synergies. The core of a holistic approach must target its actions to human-centric development, such as the WEF nexus holistic approach or the "Five Pillars Alliance" that brings together water, energy, food, health, and education as defined by the World Water Council [134]. Finally, this approach should benefit from the utilization of existing methodologies and global platforms that are commonly used to deeply analyze water, energy, food, and climate change across nations and provide country ranks.

The following section describes a proposed "new system model", its components and justification. The proposed new model addresses the WEF systems analysis from the security approach, integrated into an international platform that allows country assessment and comparison. The model aims to measure the risk, in opposition to security, based on allocation, availability and other factors affecting the WEF system composition. The WEF Nexus system is composed of four metrics and a "proxy" value for trade-off and synergies, as follows: 1) water risk, 2) food risk, 3) energy risk, 4) the disaster risk and climate change metric; and 5) a quantifiable approximating value of the trade-off and synergies applicable to the system.

A mathematical description of the system approach is proposed as follows:

$$\begin{aligned} Nexus\ Security = {} & \sum Water\ Sucurity\ Risk + \sum Energy\ Security\ Risk \\ & + \sum Food\ Security\ Risk \\ & + \sum DissasterRisk\&Clim\_Change + \ \Delta Proxi\Big(TradeOff \\ & + synergies\Big\} \end{aligned} \tag{1}$$

Furthermore, addressing this novel WEF Nexus system from the security and global perspective implies reviewing the definitions of water, food, and energy security concepts developed by international organizations and global platforms, as presented in Table 2.

Table 2
Water, Food, and Energy security concepts from international organizations and definitions of the proposed WEF system components.

WEF Nexus definitions by International Organizations	Proposed WEF system components definitions
Water security index by UN-Water "…*the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*" [135].	**Water security Index** Measures the water security based on the water risk obtained by the evaluation of the available water resources at the country scale. The water risk shows the magnitude of the degree of water allocation that is conceded or compromised to the different water users. In that sense, regions with high water risk have highly compromised their available water resources with the current demands; consequently, future scenarios of increased demand will be at probable risk of allocation [136]
Global Food Security from the Economist Impact "…*a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life*" [1]. The index applies a dynamic benchmarking model constructed from 68 indicators that measure the drivers of food security across both developing and developed countries [137].	**Food security Index from the Global Food Security Index (GFSI)** The indicator assesses food security by measuring the influence and impacts of the food sector in the energy and water systems. The international index is compound of four pillars: affordability, accessibility, and quality. It brings information of the main drivers that exert significant risk in the global food system and the interconnectedness of the food system (Global Food Security Index, 2022- The Economist Group 2022).
Energy security defined by the International Energy Agency (2014) As the interrupted availability of energy sources at an affordable price, it is a key parameter that indicates the current position and orientation of the development of any country or region in the present and future. It comprises 15 dimensions for energy security analysis: Availability, Diversity, Cost, Technology and Efficiency, Location, Timeframe, Resilience, Environment, Health, Culture, Literacy, Employment, Policy, Military, and Cyber Security [138]	**Energy security Index (GEI)** The international energy security index estimates the state of energy risk in the region in analysis, is designed to evaluate energy security risks across countries and its change over time. The energy security index is described by eight categories: Global Fuel; Fuel Imports; Energy Expenditure; Price and Market Volatility; Energy Use Intensity; Electric Power Sector; Transportation; and Environment [139].
Climate Change from Intergovernmental Panel on Climate Change (IPCC) The conceptual framework from the Climate Change 2022, Impacts, Adaptation and Vulnerability from Sixth Assessment Report of the IPCC defined risk as the interaction between climate hazard, vulnerability, and exposure; and climate changes impacts involve human society and the ecosystems, including biodiversity [140].	**Disaster and Climate Change Risk Index** This indicator aims to assess how climate change causes impacts and risks at the regional scale. The indicator categorizes the state of risk and impacts from the highest to lowest of the region in analysis. The indicator measures the risk resulting from dynamic interaction of its three components: climate hazard, vulnerability, and expositions inside the unit of analysis [136].
World Resource Institute (WRI) WRI developed a global water risk platform called Aqueduct 4.0 that presents a composite index approach, composed by physical risk quantity, quality and the regulatory and reputational risk. The water risk quantity has been chosen for the purpose of this index following the method of risk elements [136]	Three indicators were chosen from the water risk global platform, presented in Aqueduct 4.0 that best describes the proposed index: riverine flow risk, coastal flow risk and drought risk

As noted, the four concepts consider different dimensions and criteria of analysis. The idea is to quantify a "Nexus Security Index" based on a mathematical approximation of risk that describes the systems and subsystems. The aim is to find the balance between Nexus resources and scenarios. The indexes quantify the core Nexus system components coming from national or regional resources, accounting for the possibilities of disaster risk and climate change that may affect vulnerable resources and estimates a proxy value to allow trade-offs and synergies as choices. An alternative approach in the quantification of national resources should focus on optimizing in a sustainable manner the country's resources for the nexus elements as is presented in the proposed model.

$$\begin{aligned} \mathit{Alternative\ Nexus\ Security} = & \sum Max_{waterSecurity} + \sum Max_{energy\ security} \\ & + \sum Max_{foodsecurity} \\ & + \sum Min\_DissasterRisk\&Clim\_Change \\ & + \Delta Proxi\{Synergies + Tradeoff\} \end{aligned} \tag{2}$$

Table 3

Composition of nexus security index model.

Component name	Indicators	Sub indicators
Overall water risk indicator [136]	Physical risk (quantity)	Baseline water stress Interannual variability Seasonal variability Groundwater table decline
	Physical risk (quality)	Untreated connected wastewater
	Hydraulic infrastructure for agriculture	Irrigation gap infrastructure Non-irrigated agricultural area gap
	Regulatory risk	Improved/no drinking water Improved/no sanitation
Disaster and Climate change Indicator [136]	Riverine flood risk	Precipitation anomaly index
	Coastal flow risk	Percentage of the population exposed to the hazard Percentage of agricultural hectares exposed to the hazard
	Drought risk	Percent annual exceedance probability flood
Energy security indicator [139]	Global fuels	Security of oil production Security of natural gas production Security of coal production
	Fuel import	Total energy import exposure Fossil fuel import expenditures per GDP
	Energy expenditure metrics	Energy expenditures per capita Retail electricity prices Crude oil prices
	Price & market volatility	Crude oil price volatility Energy expenditure volatility
	Energy use intensity	Energy consumption per capita
	Transportation sector	Transportation energy per capita
Food indicator (Global Food Security Index, 2022- The [137])	Affordability	Cereals yields Presence of food safety net programs Agricultural trade Food safety net programs
	Availability	Access to finance and financial products for farmers Crop storage facilities Agriculture Produce Price index Road infrastructure Air, port and rail infrastructure
	Exposure	SPEI Global Drought Monitor Early-warning measures / climate-smart Agriculture National agricultural adaptation policy (Global Food security Index, 2022) Pest infestation and disease mitigation

The Nexus Security Index approach benefits from utilizing existing methodologies and global platforms commonly used to deeply analyze water, energy, food, and climate change risk across nations providing country ranks. Table 2 provides definitions of the WEF system component indexes including climate change. Consequently, since the four components constitute international indexes or risk metrics, they are described by several subcomponents, applied at the country level.

For the proposed model, each indicator contains a suitable combination of sub indicators defined at a country geographical scale for the assessment. The sub indicators maintain a uniform scale that measures security, availability, and allocation across the four main components. The weight applied for each sub indicator is a multiplying factor, which obeys experts' local knowledge of the four system components. Finally, the overall security of the components results from the weighted sum of all sub indicators, and the total Nexus security index comes from the summation of all components and the proxy value. Table 3 shows the system components, indicators and sub indicators of the new proposed WEF model.

Further development of the model is demonstrated in the following Tables as an assessment for two countries (i.e., Peru and Egypt). However, any country can estimate its own index by following the organization and composition of the four Nexus components as demonstrated in the next Tables. The following steps provides guidance on the calculation process for each indicator and sub-indicator.

To assess overall water risk, each sub-indicator should follow the methodology developed by Kuzma et al. [136], where mathematical expressions for all sub-indicators are provided. Generally, the water data requirements include a minimum of a 30-year period of analysis, performed at the basin unit level that integrates the country. The data used in the calculations should follow the temporal resolution specified in Kuzma et al.'s method, which requires either monthly or annual baseline averages applied at the unit basin level. After calculating results for one basin, it is recommended to include as many basin units as possible to best represent the country or focus on the most significant ones. The overall sub-indicator index is calculated as the average of the indices from all selected basins. The risk level, ranging from 1 to 5, is determined using a linear interpolation step between two related scales (e.g., baseline water stress to risk level). This process converts the sub-indicator value into the corresponding risk value. Finally, the overall water risk is calculated by sum of all sub-indicators in the scale of 1- 5 with the applied corresponding weight (Table 4). The applied weights should sum up to 1 and will depend on every country's special case and expert knowledge.

The methods and equations for estimating each sub-indicator in the Disaster and Climate Change Risk category are detailed in Kuzma et al. [136]. The data requirements and calculation processes are the same as those outlined for water risk. Finally, the Disaster and Climate change risk indicator is obtained by the sum of four sub-indicators, previously normalized in the 1–5 range scale (Table 5) and each sub-indicator is affected by its own respective weight. The composition of sub-indicators are novel contributions to this model, and were selected from the global water risk framework, available in the Aqueduct Water Risk Atlas [136].

Energy security risk is composed of six selected indicators and corresponding sub-indicators, defined in the International Index of Energy Security Risk Report (link to the report) developed by the Global Energy Institute. They were elected for the purpose of this model (Table 6). Each indicator contains several sub-indicators, whose values for each country are provided in the report. Their metrics are from 0 to 2000, which then are interpolated to the 0 to 5 scale, such as the 0–1000 range is considered as low risk and equivalent to the 0–2.5 scale in this context. Final score is the weighted sum of all sub- indicators with the applied weight.

(a) Food security risk indicator is composed of three selected indicators (Table 7). Each indicator contains several sub-indicators with specific metrics obtained by the referenced method, listed in Table 7. Quantitative values are provided on a country-specific

Table 4
Composition of overall water risk Indicators: components and subcomponents (Method developed in [136]).

Indicator		Sub-Indicator	Weight	Description	Indicator Range Value		Hydrologic Units (HU) - Peru			Hydrologic Units (HU) - Egypt		Risk Level		Peru			Peru Risk	Egypt		Egypt Risk
			%		Min	Max	HU 1	HU 2	HU 3	HU 1	HU 2	Value	Category	HU 1	HU 2	HU 3		HU 1	HU 2	
Overall water risk indicator	I. Physical risk (quantity)	1. Baseline Water Stress	0.15	Water stress [136]. IT Measures the ratio of total water consumption to available blue water, Total water consumption includes domestic, industrial, irrigation, and livestock consumptive uses.	0 5 20 50 75	5 25 50 75 more	0.34	0.35	103.17	100.00	136.58	<1 1–2 2–3 3–4 4–5	Very low Low Medium High Extremely high	2.36	2.40	5.00	**3.25**	5.00	5.00	**5.00**
		2. Interannual Variability (IAV)	0.13	Interannual variability [136]. It measures the average between-year variability of available water supply, including both renewable surface and groundwater supplies. Higher values indicate wider variations in available supply from year to year.	0 0.25 0.5 0.75 1	0.25 % 0.50 % 0.75 % 1 % more	0.20	0.62	0.64	0.59	1.85	<1 1–2 2–3 3–4 4–5	Very low Low Medium High Extremely high	0.82	2.48	2.55	**1.95**	2.36	7.39	**4.87**
		3. SE (SEV)	0.05	Seasonal variability [136]. Measures the average within-year variability of available water supply, including renewable surface and groundwater supplies. Higher values mean wider variations of available supply within a year.	0 0.33 0.66 1 1.33	0.33 0.66 1 1.33 3	0.35	0.79	0.76	0.32	1.32	<1 1–2 2–3 3–4 4–5	Very low Low Medium High Extremely high	1.04	2.38	2.27	**1.89**	0.96	3.97	**2.46**
		4. Groundwater Table decline (GTD)	0.05	Method describes in [136]. Measures the average decline of the groundwater table as the average change from 1990 to 2014. Units are in centimeters per year (cm/yr). Higher values indicate higher levels of unsustainable groundwater withdrawals.	 0 2 4 8	<0 2 4 8 +	−0.02	−0.39	−0.19	1.40	0.10	<1 1–2 2–3 3–4 4–5	Very low Low Medium High Extremely high	0.98	0.61	0.81	**0.80**	2.40	1.10	**1.75**
	II. Physical risk (quality)	5. Untreated Connected Wastewater (UCW)	**0.10**	Measures the percentage of domestic wastewater that is connected through a sewerage system and not treated to at least a primary treatment level. Method describes in [136]	0 30 60 90	<30 60 90 100 <100	37.30	37.30	37.30	61.39	61.39	<1 1–2 2–3 3–4 4–5	Very low Low Medium High Extremely high	1.24	1.24	1.24	**1.24**	2.05	2.05	**2.05**
	III. Hydraulic infrastructure for agriculture	6. Irrigation Gap Infrastructure (IGI)	0.10	Sum of unlined hydraulic infrastructure / Tot Hydraulic infrastructure (natural + builded) (%)	0 20 40 60 80	20 40 60 80 100	65.00	67.00	20.00	30.00	30.00	<1 1–2 2–3 3–4 4–5	acceptable Regular Unfavorable Highly unfavorable critical	3.75	3.35	1.00	**2.70**	1.50	1.50	**1.50**
		7. Non-Irrigated Land (NIL)*	0.13	Total Land with no irrigation/ Total Potential cultivated land) %	0 20 40 60 80	20 40 60 80 100	15.00	28.00	18.00	5.00	5.00	<1 1–2 2–3 3–4 4–5	Acceptable Regular Unfavorable Highly unfavorable critical	0.75	1.40	0.90	**1.02**	0.25	0.25	**0.25**
	IV. Regulatory risk	8. Improved /No drinking water (IDW)	0.15	% Population without access to potable water /Total population [136]. Unimproved/no drinking water reflects the percentage of the population collecting drinking water from an	0 2.5 5	<2.5 5 10	23.88	23.27	20.27	1.64	1.39	<1 1–2 2–3	Acceptable Regular Unfavorable	4.20	4.22	4.02	**4.15**	0.39	*0.15*	**0.27**

(*continued on next page*)

Table 4 (*continued*)

Indicator	Sub-Indicator	Weight	Description	Indicator Range Value		Hydrologic Units (HU) - Peru			Hydrologic Units (HU) - Egypt		Risk Level		Peru			Peru Risk	Egypt		Egypt Risk
		%		Min	Max	HU 1	HU 2	HU 3	HU 1	HU 2	Value	Category	HU 1	HU 2	HU 3		HU 1	HU 2	
			unprotected dug well or spring, or directly from a river, dam, lake, pond, stream, canal, or irrigation canal	10	20						3–4	Highly unfavorable							
				20	more						4–5	critical							
	9. Improved /No sanitation (IS)	0.15	% Population with no sanitation / Total Population [136] Percentage of the population using pit latrines without a slab or platform, hanging/ bucket latrines, or directly disposing human waste in fields, forests, bushes, open bodies of water, beaches, other open spaces, or with solid waste (WHO and UNICEF 2017).	0	<2.5	34.15	35.97	29.23	4.54	3.34	<1	Aceptable	4.77	4.85	4.55	**4.72**	1.86	1.44	**1.65**
				2.5	5						1–2	Regular							
				5	10						2–3	Unfavorable							
				10	20						3–4	Highly unfavorable							
				20	more						4–5	critical							
Water Risk	*1.00*															**2.72**			**2.24**

basis, while qualitative ratings depend on the expertise and experience of the respective country. Then, metrics are interpolated to the 1 – 5 scale accordingly. The final score is the weighted sum of all sub-indicators.

(b) The final index is the Nexus security value obtained by the average of the four indicators from previous tables as shown in the Table 8. The final Nexus security index is a measure of risk in the scale from 0 to 5 where low values mean low risk or high security and values close to 5 means low security or high risk. The Nexus security final values for both countries are in the range from 2 to 3 indicating a medium level of risk, which will be the threshold value for the trade-off analysis.

(a) Trade-offs were evaluated using sensitivity analysis to account for resource allocation among water, energy, and food sectors. This included assessing the impact of reallocating water to energy, water to food, energy to food, and considering the effects of disaster risk and climate change on water and food security. The Fig. 3 illustrates the sensitivity analysis performed on the Nexus final security score, applied to the case of Peru. The analysis was conducted in a matrix format for each combination, where each WEF index was increased incrementally from its actual value to a maximum risk level of 5, and compared to the corresponding WEF index, which was decreased from its actual value to a minimum risk level. This approach simulates the effects of increasing one resource's usage on the other resources, demonstrating how risk reduction or security improvement in one area impacts the other.

The trade-off analysis between water and energy shows that up to a 50 % increase in water use for energy can be accommodated without pushing the final Nexus index into high-risk values (>3). In contrast, the water-for-food trade-off demonstrates lower sensitivity, where up to a 60 % increase in water use for food production keeps the Nexus security within a medium-risk range (2, 3). Similarly, the trade-off between energy and food exhibits low sensitivity, allowing resource exchange without compromising the final Nexus security score. However, the trade-offs involving disaster risk and climate change impacts on water and food are highly sensitive. In both cases, increasing disaster and climate change risks directly elevate water and food risks, with Nexus index values exceeding 3 in all scenarios. This heightened sensitivity underscores the vulnerability of the Nexus to these changes, making it more susceptible to variations in disaster and climate risk.

9. The nexus security index tool for the achievement of SDGs

The proposed Nexus Security Index is a tool designed to assess deficiencies in water, food, and energy security, as well as disaster and climate change risks. This tool enhances the analysis of systems management effectiveness, aiming to evaluate how countries allocate resources to their populations and provide protection from natural disasters. The following section illustrates the application of the Nexus tool in Peru by analyzing the results of the risk indicators and sub-indicators related to water, energy, food, disaster, and climate change. It also provides recommendations for government entities to address these risks and, consequently, contribute to the achievement of the SDGs. These analyses aim to target SDGs 6, 7, 2, 8 and 13, as follows:

The overall water risk results in Table 4 determine two high-risk levels, highlighting the need for actions by governmental entities. The sub-indicators of "Improved/No Drinking Water" and "Improved/No Sanitation" reveal a significant lack of infrastructure to provide drinking water and sanitation to people. These risks should prompt an immediate response from the government in the form of policies, programs, and projects to prioritize and execute physical interventions in water and sanitation, focusing on the most vulnerable populations. Implementing these actions will align with SDG 6, targeting goals 6.1, 6.2, 6.3, and 6.4.

Table 5
Composition of disaster and climate change risk indicator.

	Sub-Indicator	Coef. Part	Description	Indicator Range Value		Hydrologic Units (HU) - Peru			Hydrologic Units (HU) - Egypt		Risk Level		Regions			Peru Risk	Regions		Egypt Risk
	Name	%		Min	Max	HU1	HU2	HU3	HU1	HU2	Valor	Category	HU1	HU2	HU3		HU1	HU2	
II. Disaster and Climate change risk indicator	1. Riverine flow risk	0.33	Measures the percentage of population expected to be affected by Riverine flooding in an average year (Method shown by [136])	0.00	0.12	0.68	0.62	1.04	6.73	1.68	<1	Low	3.09	3.00	3.61	**3.24**	4.16	4.01	**4.08**
				0.12	0.30						1–2	Low-medium							
				0.30	0.62						2–3	medium to high							
				0.62	1.30						3–4	high							
				1.30	more						4–5	Extremely high							
	3. Costal flow risk	0.33	Coastal flood risk measures the percentage of the population expected to be affected by coastal flooding in an average year, accounting for existing flood protection standards (Method shown by [136])	0	0.001	0.00	0.00	0.00	0.00	0.00	<1	Low	0.00	0.00	0.00	**0.00**	1.34	0.01	**0.67**
				0.001	0.007						1–2	Low-medium							
				0.007	0.04						2–3	medium to high							
				0.04	0.22						3–4	high							
				0.22	>						4–5	Extremely high							
	3. Drought risk	0.33	Measures the product between the likeliness to occur drought, the population and assets exposed, and the vulnerability of the population and assets to adverse effects. (Method developed by	0	0.2	0.25	0.40	0.45	0.69	N.A	<1	Low	1.24	2.00	2.23	**1.82**	3.44	**N.A**	**3.44**
				0.2	0.4						1–2	Low-medium							
				0.4	0.6						2–3	medium to high							
				0.6	0.8						3–4	high							
				0.8	1						4–5	Extremely high							
																1.67			**2.70**

Table 6
Composition of energy risk indicator: components and subcomponents.

Energy Indicator	Weight	Indicator	Definition	Sub indicator	Sub-indictor Range (*)		Peru	Egypt	Scale		Peru Risk	Egypt Risk
Energy security indicator	0.3	Global fuels	"Accounts for the reliability and diversity of global reserves and supplies of oil, natural gas, and coal. Higher reliability and diversity mean a lower risk to energy security" [139]	Security of oil production	0	1000	837	819	0–2.5	low risk	2.093	2.048
					1000	2000			2.5 - 5	high risk		
				Security of natural gas production	0	1000	917	908	0–2.5	low risk	2.293	2.270
					1000	more			2.5 - 5	high risk		
				Security of coal production	0	1000	1212	1235	0–2.5	low risk	3.030	3.089
					1000	2000			2.5 - 5	high risk		
	0.25	Fuel import	"Measure the exposure of the country's economy to unreliable and concentrated supplies of oil and natural gas and import costs (not related to the number of imports). Higher reliability and diversity and lower costs mean a lower risk to energy security" [139]	Total energy import exposure	0	1000	375	192	0–2.5	low risk	0.937	0.481
					1000	2000			2.5 - 5	high risk		
				Fossil fuel import expenditures per GDP	0	1000	267	269	0–2.5	low risk	0.667	0.673
					1000	2000			2.5 - 5	high risk		
	0.15	Energy expenditure metrics	"Measure the magnitude of energy costs to national economies and the exposure of consumers to price shocks. Lower costs and exposure mean a lower risk to energy security " [139]	Energy expenditures per capita	0	1000	143	221	0–2.5	low risk	0.356	0.552
					1000	2000			2.5 - 5	high risk		
				Retail electricity prices	0	1000	848	831	0–2.5	low risk	2.121	2.078
					1000	2000			2.5 - 5	high risk		
				Crude oil prices	0	1000	635	595	0–2.5	low risk	1.589	1.487
					1000	2000			2.5 - 5	high risk		
	0.1	Price & market volatility	"Measure the susceptibility of national economies to large swings in energy prices. Lower volatility means a lower risk to energy security" [139]	Crude oil price volatility	0	1000	830	811	0–2.5	low risk	2.075	2.027
					1000	2000			2.5 - 5	high risk		
				Energy expenditure volatility	0	1000	524	971	0–2.5	low risk	1.310	2.426
					1000	2000			2.5 - 5	high risk		
	0.1	Energy use intensity	"Measure energy use in relation to population and economic output. Lower use of energy by industry to produce goods and services means a lower risk to energy security" [139]	Energy consumption per capita	0	1000	152	180	0–2.5	low risk	0.380	0.450
					1000	2000			2.5 - 5	high risk		
	0.1	Transportation sector	"Measure efficiency of energy use in the transport sector per unit of GDP and population. Greater efficiency means a lower risk to energy security" [139]	Transportation energy per capita	0	1000	187	166	0–2.5	low risk	0.468	0.415
					1000	2000			2.5 - 5	high risk		
Energy security indicator	**1**										**3.66**	**3.66**

Disaster and Climate change indicator results reveal a high probability of people in risk of riverine flow. The warning should proceed to immediate actions taken by responsible entities in the government to identify the most critical zones of risk, leading to allocate economic resources to build riverine flood protection infrastructure, dredging and re-channeling activities in the riverbed, and executing programs for people relocation to a safer place. The actions taken will target SDG 13, specifically the goals 13.1 and 13a.

The energy risk indicator highlights Peru as a medium-risk country in terms of energy security. One significant risk is coal production security, while less significant risks include oil and natural gas production security, both considered non-sustainable energy sources. The main sources of energy in Peru are derived from hydropower and natural gas, accounting for 52.5 % and 39.43 %, respectively, with coal production considered negligible. Despite the differences in the nature of energy sources, the indicators reveal a relative medium risk of energy security stemming from oil and natural gas production. This analysis should lead and encourage governmental entities to enhance national, clean, sustainable energy production, such as hydropower, as the most common source. Policy-established mechanisms fostering private investment in technological advances for clean, sustainable energy production will be highly effective. Execution of these actions will align with SDG 7, targeting goals 7.1, 7.2, and 7.3, ensuring energy access for all.

The food security indicator reveals an overall medium risk in terms of accessing food security. Nevertheless, some sub-indicators with significant weight and higher risk are highlighted in this analysis. These include cereal yield production, the presence of food safety programs, road, rail, air, and port infrastructure, political stability, and drought monitoring. Actions taken by responsible entities should focus on research, technology, and water infrastructure development to increase national cereal yield, ensuring it meets the population's needs in areas with low food access. Economic investment and effective project

Table 7
Composition of food security risk indicator.

Food Indicator	Indicator	Weight	Sub indicator	Definition	Sub-indictor Range		Peru	Egypt	Scale	Description	Peru Risk	Egypt Risk
Food security indicator	Affordability	0.2	Cereals yields (2022) From: Food and Agriculture Organization of the United Nations (2023) – with major processing by Our World in Data	Cereal yield (Ton / Ha)	7	8	4.63	7.42	0.64 - 0	very low risk	2.16	0.37
					5.3	7			1.73 - 0.64	low risk		
					3.6	5.3			3.6 - 1.73	medium risk		
					1.9	3.6			3.91 - 3.6	unfavorable		
					0.2	1.9			5–3.91	critical		
		0.01	Presence of food safety net programs (Global Food security Index, 2022)	Qualitative rating 0–1; 1=best (average value 2012 –2022)	0.5	1	1	1	0 - 0.2.5	low risk	5	5
					0	0.5			2.5 - 5	high risk		
	Availability	0.01	Access to finance and financial products for farmers (Global Food security Index, 2022)	Qualitative rating 0–2; 2=best (average value 2012 –2022)	1	2	1	1	0 - 2.5	low risk	2.5	2.5
					0	1.0			2.5 - 5	high risk		
		0.05	Crop storage facilities (Global Food security Index, 2022)	Qualitative rating 0–1; 1=best	0.5	1	0.4	1	0 - 0.2.5	low risk	2.199	0
					0	0.5			2.5 - 5	high risk		
		0.15	Agriculture Produce Price index (2014–2016 = 100) (2017) From: FAO (https://data.apps.fao.org/catalog/dataset/faostat-pp/resource/4a688311–7edb-4f45-ab3f-370be750eeaf)	Producer price indices (PPI) measure the rate of change in prices of products sold as they leave the producer over time	0	65.48	99.38	155.75	0 - 0.192	low risk	0.291	0.457
					65.48	93.57			0.192 - 0.274	low risk		
					93.57	105.81			0.274 - 0.310	moderate		
					105.81	124.57			0.310 - 0.365	moderate		
					124.57	157.19			0.365 - 0.461	high risk		
					157.57	226.79			0.461 - 0.665	high risk		
					226.79	318.92			0.665–0.935	extremely high		
					318.92	1705.63			0.935 - 5	extremely high		
		0.15	Road infrastructure (Global Food security Index, 2022)	Qualitative rating 0–4; 4=best (average value 2012 –2022)	2	4	2	2	0 - 2.5	low risk	2.5	2.5
					0	2.0			2.5 - 5	high risk		
		0.14	Air, port and rail infrastructure (Global Food security Index, 2022)	Rating 0–4; 0=poor, 4=very good (average value 2012 –2022)	2	4	1.7	2.6	0 - 2.5	low risk	2.88	1.75
					0	2.0			2.5 - 5	high risk		
		0.05	Political stability and absence of violence/terrorism estimate (2022). From DataBank Worldwide Governance Indicators- World Bank (https://databank.worldbank.org/source/worldwide-governance-indicators/Series/PV.EST#advancedDownloadOptions)	Estimate 5 level ranking	1	1.8	−0.4	N.A	0 - 0.930	stability	2.56	N.A
					0.4	1			0.930 - 1.628	low instability		
					−0.2	0.4			1.628 - 2.326	Moderate		
					−0.9	−0.2			2.326 - 3.140	unfavorable		
					−2.5	−0.9			3.140 - 5	critical		
		0.01	Corruption Perceptions Index (CPI)	Measures how corrupt each country's public sector is perceived to be, according to experts and businesspeople (0 - 100)	80	100	33	35	0 - 1	clean	3.35	3.25
					60	79.99			1 - 2	low		
					40	59.99			2 - 3	moderate		
					20	39.99			3 - 4	corrupted		
					0	19.99			4 - 5	highly corrupted		
	Exposure	0.2	SPEI Global Drought Monitor (SPEI time scale = 1; Date (1/1955 - 4/2024)	Risk rating −2.33 - 2.33	1.65	2.33	−2.33	−2.33	0.730 - 0	extreme wet	5	5
					1.28	1.65			1.127 - 0.730	moderate wet		
					0.84	1.28			1.599 - 1.127	abnormal wet		
					0	0.84			2.5 - 1.599	neutral		
					−0.84	0			3.401 - 2.5	abnormal dry		
					−1.28	−0.84			3.873 - 3.401	moderate		

(*continued on next page*)

Table 7 (*continued*)

				−1.65	−1.28			4.270 - 3.873	severe drought		
				−2.33	−1.65			4.270 - 5	extreme drought		
	0.01	Early-warning measures / climate-smart Agriculture (Global Food security Index, 2022)	Qualitative rating 0–2; 2=best (average value 2012 –2022)	1	2	0	0	0 - 2.5	low risk	0	0
				0	1.0			2.5 - 5	high risk		
	0.01	National agricultural adaptation policy (Global Food security Index, 2022)	Qualitative rating 0–2; 2=best (average value 2012 –2022)	1	2	2	2	0 - 2.5	low risk	5	5
				0	1.0			2.5 - 5	high risk		
	0.01	Pest infestation and disease mitigation (Global Food security Index, 2022)	Qualitative rating 0–1; 1=best (average value 2012 –2022)	2	1	0	0	0 - 2.5	low risk	0	0
				0	0.5			2.5 - 5	high risk		
Food security indicator	1									**2.6**	1.920

Table 8
Final index and sensitivity analysis of trade-off analysis.

Indicator	Peru	Egypt
Water risk	2.72	2.24
Disaster & climate change risk	1.66	2.70
Energy risk	3.66	3.66
Food risk	2.5	1.52
Nexus security	2.64	2.53

execution to improve road, rail, and port infrastructure will significantly enhance the accessibility and affordability of food. Additionally, drought prevention programs should include economic incentives for farmers to adopt modern irrigation systems, such as drip or sprinkler irrigation, and community infrastructure benefits, such as building rainwater harvesting systems, reservoirs, and medium-sized dams. These measures would increase water supply during the rainy season and make it available for use during droughts. The execution of these actions will align with the achievement of SDG 2, targeting goals 2.1, 2.2, 2.3, and 2.4.

(a) Finally, the interlinkages among the four sectors of the WEF Nexus security, through integrated and concrete actions, will promote economic growth at local and regional levels, ensuring inclusive opportunities for youth and women. This aligns with SDG 8, specifically targeting goals 8.1, 8.2, 8.5, and 8.6

10. Conclusions

This review highlights the major milestones of the WEF Nexus research, develop a comprehensive evaluation of the main WEF Nexus frameworks and tools, the importance of the WEF Nexus to achieve SDGs, gaps and challenges of the WEF Nexus, and the need for a novel approach to the WEF Nexus.

SDGs are expected to be achieved by 2030, but most countries have made limited progress toward reaching these goals and targets. Achieving the SDGs requires a comprehensive understanding of resource management and their linkages among them at local, regional, and global scales. The Water-Energy-Food (WEF) Nexus approach has proven to be an effective platform for fostering a better understanding of resource management. By adopting the WEF Nexus approach, decision-makers can implement more sustainable practices in managing the resources, thereby contributing significantly to the achievement of the SDGs at both local and regional levels in terms of water, energy, food and climate change goals (SDGs 6,7,2,8 and 13)

Addressing WEF resource challenges through successful implementation of the WEF Nexus approach requires holistic thinking, stakeholder involvement, appropriate tools, developing effective models, and knowledge of emerging hotspots. The current gaps in Nexus are the lack of an international consensus on its metrics components and subcomponents applied to a suitable regional or country scale. The gaps retrain the process of measuring performance and developing comparisons by country indexes and metrics with a global, unique analytical platform, and a set of criteria. The need for a novel system is addressed in this paper. The proposed new system aims to integrate water - energy – food, disaster risk and climate change into an international platform that allows country assessment and comparison to cope with the lack of global consensus. The mentioned Nexus system from the global/security perspective brings an international base and comprehensive uniform approach, given the diverse and complex interpretations of the food, water, and energy security metrics.

Lessons learned from this review highlight five key points to summarize this work:

1. The WEF Nexus time frame is dynamic and engaged with international organizations to find nexus solutions and achieve SDGs.

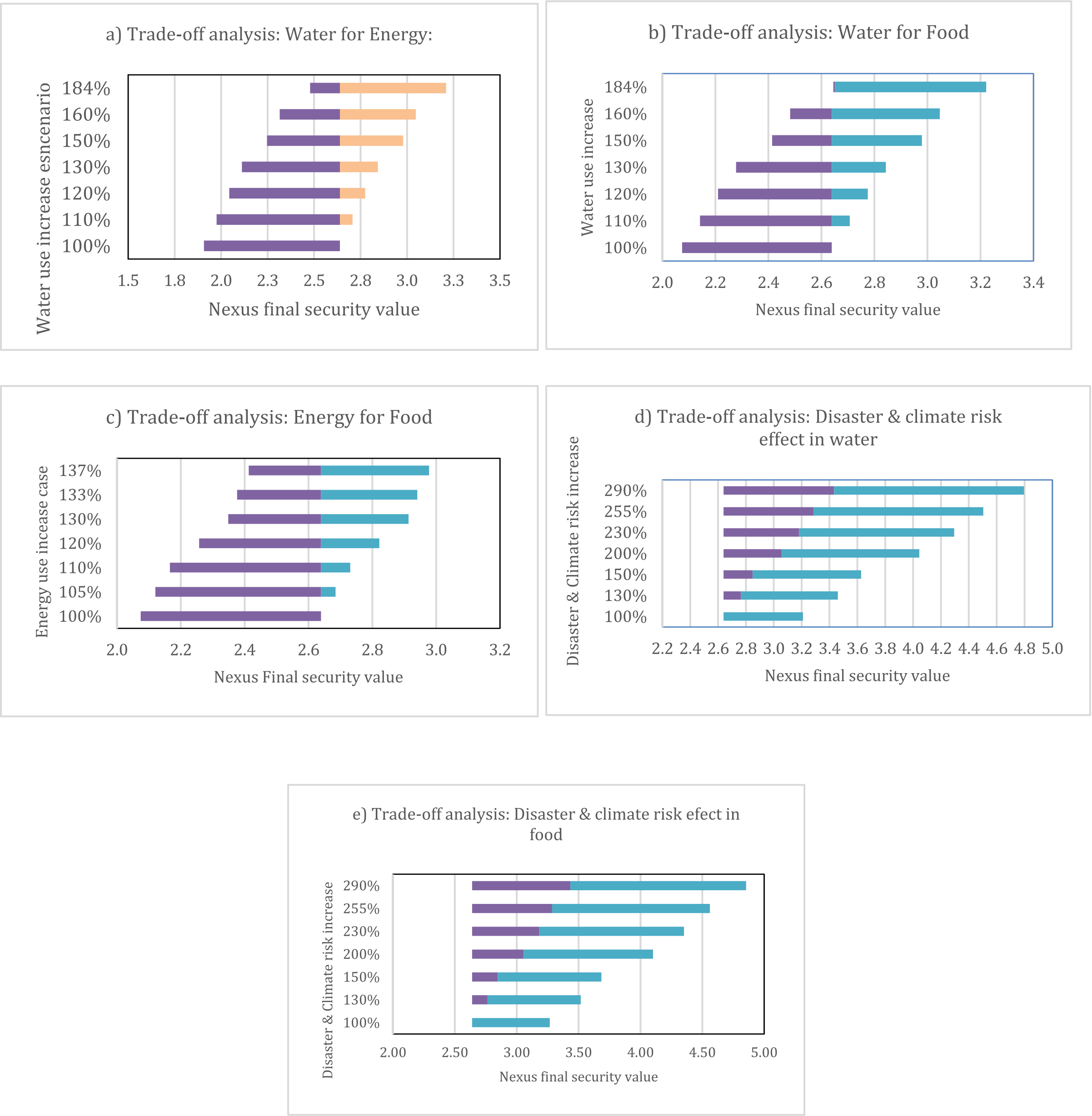

Fig. 3. The sensitivity analysis performed on the Nexus final security score to represent trade-off analysis between (a) water for energy; (b) water for food; (c) energy for food; (d) disaster & climate change risk in water; (e) disaster & climate risk effect in food.

2. WEF frameworks, tools, and models offer an integrated approach for different scales, grounded on sciences, economy, political, and human disciplines that are useful for local, regional, and national applications. Multi-centric approaches enhance the value and purpose of Nexus frameworks. Comprehensive models and tools estimate resource requirements for both present and future scenarios. These tools can incorporate interlinkages, trade-offs, sensitivity analyses, societal and economic impacts, and decision support systems for governmental entities, further increasing their utility and effectiveness.
3. Among the nexus gaps and challenges, natural-driven crises such as water scarcity, energy shocks, food crises, and climate change remain the most significant to address and manage; governance is categorized as a major gap in the nexus approach due to the lack of grounded tools and frameworks.

The developed Nexus security index is described as an international and comprehensive model at a global scale that provides a critical framework for understanding and addressing the complexities of water, energy, and food interdependencies. The model utilizes a four-component, multicenter and equal pillars conceptual framework, based on water, energy, and food resources and the component of disaster risk & climate change, which measure the availability, security and allocation of resources based on 6 indicators and 38 sub indicators.

The proposed WEF Nexus Index can be utilized as a quantitative and qualitative tool that helps highlight country disparities, vulnerabilities, and strengths. The tool can be viewed either as an independent metric for each country or as a combined data set for metric comparison among countries. These analyses are intended to support the decision-making process, serving policymakers, researchers, and stakeholders to enhance the sustainability and security of these vital resources. The WEF Nexus Index framework also provides an opportunity to create an integrated security-based development index on a per-country basis. The application of the Nexus Index tool assesses system management by providing a meaningful and comprehensive analysis of countries' effectiveness to allocate water, food, and energy resources to people, as well as to reduce the risk of disaster and climate change. Its application and implementation with concrete actions will potentially lead to the achievement of the SDGs 6, 7, 2, 8 and 13 as demonstrated in this study. Therefore, the present study supports the usefulness of the tools as a mean to contribute to the achievement of the mentioned SDGs.

CRediT authorship contribution statement

C. Yupanqui: Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **N. Dias:** Writing – original draft, Resources, Formal analysis, Conceptualization. **M.R. Goodarzi:** Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **S. Sharma:** Visualization, Investigation, Conceptualization. **H. Vagheei:** Writing – review & editing, Supervision. **Rabi Mohtar:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] FAO, The State of Food Insecurity in the World 2001, FAO, Rome, 2011.

[2] FAO, IFAD, UNICEF, WFP, WHO, In Brief to The State of Food Security and Nutrition in the World 2021: Transforming food Systems For Food security, Improved Nutrition and Affordable Healthy Diets For All, FAO, Rome, 2020.

[3] UN-Water. (2021). Summary progress update 2021: SDG 6 – water and sanitation for all. https://www.unwater.org/sites/default/files/app/uploads/2021/12/SDG-6-Summary-Progress-Update-2021_Version-July-2021a.pdf.

[4] Ritchie, H., Roser, M., & Rosado, P. (2022). Energy. Published online at OurWorldInData.org.

[5] Ritchie, H., & Max, R. (2021). Clean Water and Sanitation.

[6] H.K. Bahati, A. Ogenrwoth, J.I. Sempewo, Quantifying the potential impacts of land-use and climate change on hydropower reliability of Muzizi hydropower plant, Uganda, J. Water Clim. Change (2021), https://doi.org/10.2166/wcc.2021.273.

[7] M.R. Goodarzi, H. Vagheei, R.H. Mohtar, The impact of climate change on water and energy security, Water Supply 20 (7) (2020) 2530–2546.

[8] H. Jemmali, R. Morrar, M.S. Ben Aissa, The dynamic nexus between climate changes, agricultural sustainability, and food-water poverty in a panel of selected MENA countries, J. Water Clim. Change 12 (1) (2021) 1–17.

[9] J.D. Sachs, G. Lafortune, G. Fuller, The SDGs and the UN Summit of the Future, Dublin University Press, 2024, https://doi.org/10.25546/108572. Sustainable Development Report 2024. SDSN.

[10] J. Sušnik, C. Staddon, Evaluation of water-energy-Food (WEF) Nexus research: perspectives, challenges, and directions for future research, J. Am. Water Resour. Assoc. 58 (6) (2022) 1189–1198, https://doi.org/10.1111/1752-1688.12977.

[11] T.R. Albrecht, A. Crootof, C.A. Scott, The water-energy-food nexus: a systematic review of methods for nexus assessment, Environ. Res. Lett. 13 (4) (2018) 043002, https://doi.org/10.1088/1748-9326/aaa9c6.

[12] K.S. Rezaei, F. Celico, Analysis of pros and cons in using the water–energy–food nexus approach to assess resource security: a review, Sustainability 16 (2024) 2605, https://doi.org/10.3390/su16072605.

[13] B. Daher, R.H. Mohtar, Water-energy-food sustainable development goals in Morocco, W. L Filho, A. M. Azul, L. Brandli, A. L Salvia, & T. Wall (Eds.). Clean Water and Sanitation (Encyclopedia of the UN Sustainable Development Goals), Springer, 2021, https://doi.org/10.1007/978-3-319-70061-8_133-1.

[14] J.B.S.O. De Andrade, I.I. Berchin, J. Garcia, S. da Silva Neiva, A.V. Jonck, R. A. Faraco, W.S. de Amorim, J.M.P. Ribeiro, A literature-based study on the water–energy–food nexus for sustainable development, Stoch. Environ. Res. Risk Assess. 35 (1) (2021) 95–116, https://doi.org/10.1007/s00477-020-01907-5.

[15] A. Del Borghi, L. Moreschi, M. Gallo, Circular economy approach to reduce water–energy–food nexus, Curr. Opin. Environ. Sci. Health 13 (2020) 23–28, https://doi.org/10.1016/j.coesh.2019.10.002.

[16] A. Endo, K. Burnett, P. Orencio, T. Kumazawa, C. Wada, A. Ishii, I. Tsurita, M. Taniguchi, Methods of the water-energy-food nexus, Water 7 (10) (2015) 5806–5830 (Basel).

[17] A. Endo, M. Yamada, Y. Miyashita, R. Sugimoto, A. Ishii, J. Nishijima, M. Fujii, T. Kato, H. Hamamoto, M. Kimura, T. Kumazawa, J. Qi, Dynamics of water–energy–food nexus methodology, methods, and tools, Environ. Sci. Health 13 (2020) 46–60.

[18] A. Purwanto, J. Sušnik, F.X. Suryadi, C.D. Fraiture, Water-energy-food nexus: critical review, practical applications, and prospects for future research, Sustainability 13 (4) (2021) 1919.

[19] G.B. Simpson, G.P. Jewitt, The development of the water-energy-food nexus as a framework for achieving resource security: a review, Front. Environ. Sci. 7 (8) (2019), https://doi.org/10.3389/fenvs.2019.00008.

[20] C. Zhang, X. Chen, Y. Li, W. Ding, G. Fu, Water-energy-food nexus: concepts, questions, and methodologies, J. Clean. Prod. 195 (2018) 625–639.

[21] M. Bazilian, H. Rogner, M. Howells, S. Hermann, D. Arent, D. Gielen, K. K. Yumkella, Considering the energy, water and food nexus: towards an integrated modelling approach, Energy Policy 39 (12) (2011) 7896–7906, https://doi.org/10.1016/j.enpol.2011.09.039.

[22] M.B. Beck, R.V. Walker, On water security, sustainability, and the water-food-energy-climate nexus, Front. Environ. Sci. Eng. 7 (5) (2013) 626–639, https://doi.org/10.1007/s11783-013-0576-8.

[23] A. Bhaduri, C. Ringler, I. Dombrowski, R. Mohtar, W. Scheumann, Sustainability in the water–energy–food nexus, Water Int. 40 (5–6) (2015) 723–732, https://doi.org/10.1080/02508060.2015.1096110.

[24] D. Conway, E.A. Van Garderen, D. Deryng, S. Dorling, T. Krueger, W. Landman, B. Lankford, K. Lebek, T. Osborn, C. Ringler, J. Thurlow, Climate and southern Africa's water–energy–food nexus, Nat. Clim. Change 5 (9) (2015) 837–846, https://doi.org/10.1038/nclimate2735.

[25] J. Dargin, B. Daher, R.H. Mohtar, Complexity versus simplicity in water-energy-food nexus (WEF) assessment tools, Sci. Total Environ. 650 (2019) 1566–1575, https://doi.org/10.1016/j.scitotenv.2018.09.172.

[26] A. Flammini, M. Puri, L. Pluschke, O. Dubois, Walking the Nexus talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy For All Initiative, FAO, 2014.

[27] Hoff, H. (2011). Understanding the nexus: Background paper for the Bonn conference 2011. Stockholm Environment Institute.

[28] H. Leck, D. Conway, M. Bradshaw, J. Rees, Tracing the water-energy-food nexus: description, theory and practice, Geogr. Compass. 9 (8) (2015) 445–460, https://doi.org/10.1111/gec3.12222.

[29] J. Pittock, K. Hussey, S. McGlennon, Australian climate, energy and water policies: conflicts and synergies, Aust. Geogr. 44 (1) (2013) 3–22, https://doi.org/10.1080/00049182.2013.765345.

[30] World Economic Forum. (2011a). Water security: the water-energy-food-climate nexus. http://www.WEForum.org/reports/water-security-water-energy-food-climate-nexus.

[31] A. Endo, I. Tsurita, K. Burnett, P.M. Orencio, A review of the current state of research on the water, energy, and food nexus, J. Hydrol. Reg. Stud. 11 (2017) 20–30, https://doi.org/10.1016/j.ejrh.2017.03.001.

[32] J. Liu, V. Hull, C. Godfray, D. Tilman, P. Gleick, H. Hoff, C. Pahl-Wostl, Z. Xu, M. G. Chung, J. Sun, S. Li, Nexus approaches to global sustainable development, Nat. Sustain. 1 (2018), https://doi.org/10.1038/s41893-018-0135-8.

[33] C.A. Scott, M. Kurian, J.L. Wescoat, The water-energy-food nexus: enhancing adaptive capacity to complex global challenges, M. Kurian & R. Ardakanian (Eds.). Governing the Nexus, Springer, 2015, pp. 15–30, https://doi.org/10.1007/978-3-319-05747-7_2.

[34] L. Sachs, D. Silk, Food and Energy: Strategies for Sustainable Development, United Nations University Press, 1990.

[35] R. Estoque, Complexity and diversity of nexuses: a review of the nexus approach in the sustainability context, Sci. Total Environ. 853 (1) (2023).

[36] C.A. Scott, The water–energy–climate nexus: resources and policy outlook for aquifers in Mexico, Water Resour. Res. (6) (2011) 47, https://doi.org/10.1029/2011WR010805.

[37] World Economic Forum. (2011b). Global risks 2011. http://reports.WEForum.org/global-risks-2011/.

[38] D.M. Kammen, Turning words into action on climate change, Carbon Manage 4 (2) (2013) 139–142, https://doi.org/10.4155/cmt.13.6.

[39] B.A. McCarl, Y. Yang, K. Schwabe, B.A. Engel, A.H. Mondal, C. Ringler, E. N. Pistikopoulos, Model use in WEF nexus analysis: a review of issues, Curr. Sustain./Renew. Energy Rep. 4 (3) (2017) 144–152, https://doi.org/10.1007/s40518-017-0078-0.

[40] R. Lawford, J. Bogardi, S. Marx, S. Jain, C.P. Wostl, K. Knüppe, C. Ringler, F. Lansigan, F. Meza, Basin perspectives on the water-energy-food security nexus, Curr. Opin. Environ. Sustain. 5 (6) (2013) 607–616.

[41] Mohtar, R., & Rosen, R.A. (2015). Resource nexus: water, energy, food. The Texas A&M University System.

[42] F.P. Melo, L. Parry, P.H. Brancalion, S.R. Pinto, J. Freitas, A.P. Manhães, P. Meli, G. Ganade, R.L. Chazdon, Adding forests to the water-energy-food nexus, Nat. Sustain. 4 (2) (2021) 85–92.

[43] E.M. Biggs, E. Bruce, B. Boruff, J.M. Duncan, J. Horsley, N. Pauli, K. McNeill, A. Neef, F. Van Ogtrop, J. Curnow, B. Haworth, Sustainable development and the water–energy–food nexus: a perspective on livelihoods, Environ. Sci. Policy 54 (2015) 389–397, https://doi.org/10.1016/j.envsci.2015.08.002.

[44] Wicaksono, A., Jeong, G., & Kang, D. (2015). A development of simulation model for water, energy, and food nexus. Korean Society of Civil Engineers Conference Proceedings, 67–68.

[45] R. Mohtar, B. Daher, Water-energy-food nexus framework for facilitating multi-stakeholder dialogue, Water Int. (2016), https://doi.org/10.1080/02508060.2016.1149759.

[46] T.R. Albrecht, A. Crootof, C.A. Scott, Trends in the Development of Water-Energy-Food Nexus Methods, May 29–June 3, International Water Resources Association (IWRA), Cancun, Quintana Roo, Mexico, 2017.

[47] C. Ringler, A. Bhaduri, R. Lawford, The nexus across water, energy, land, and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5 (6) (2013) 617–624.

[48] Q. Liu, Interlinking climate change with water-energy-food nexus and related ecosystem processes in California case studies, Ecol. Process. 5 (14) (2016), https://doi.org/10.1186/s13717-016-0058-0.

[49] International Centre for Integrated Mountain Development (ICIMOD), Contribution of Himalayan Ecosystems to Water, Energy, and Food Security in South Asia: A Nexus Approach, ICIMOD, Kathmandu, Nepal, 2012.

[50] L. Bizikova, D. Roy, D. Swanson, H.D. Venema, M. McCandless, The Water–Energy–Food Security Nexus: Towards a Practical Planning and Decision-Support Framework For Landscape Investment and Risk Management, International Institute for Sustainable Development, 2013.

[51] M. Al-Saidi, N.A. Elagib, Towards understanding the integrative approach of the water, energy, and food nexus, Sci. Total Environ. 574 (2017) 1131–1139, https://doi.org/10.1016/j.scitotenv.2016.09.046.

[52] G.B. Simpson, G.P. Jewitt, W. Becker, J. Badenhorst, S. Masia, A.R. Neves, P. Rovira, V. Pascual, The Water-Energy-Food Nexus Index: a tool to support integrated resource planning, management and security, Front. Water 4 (2022), https://doi.org/10.3389/frwa.2022.825854.

[53] M. Li, Q. Fu, V.P. Singh, Y. Ji, D. Liu, C. Zhang, T. Li, An optimal modelling approach for managing agricultural water-energy-food nexus under uncertainty, Sci. Total Environ. 651 (2019) 1416–1434.

[54] R. Mohtar, The importance of the water-energy-food nexus in the implementation of the sustainable development goals (SDGs), Policy Brief (2016). OCP Policy Center.

[55] M.E. Webber, Thirst For Power: Energy, Water, and Human Survival, Yale University Press, 2016.

[56] A. Wicaksono, G. Jeong, D. Kang, Water, energy, and food nexus: review of global implementation and simulation model development, Water Policy 19 (2017) 440–462.

[57] C. Taguta, A. Senzanje, Z. Kiala, M. Malota, T. Mabhaudhi, Water-energy-food Nexus tools in theory and practice: a systematic review, Front. Water 4 (2022), https://doi.org/10.3389/frwa.2022.837316.

[58] K.N. Le, M.K. Jha, M.R. Reyes, J. Jeong, L. Doro, P.W. Gassman, L. Hok, J.C. De Moraes, S. Boulakia, Evaluating carbon sequestration for conservation agriculture and tillage systems in Cambodia using the EPIC model, Agric. Ecosyst. Environ. 251 (2018) 37–47.

[59] B.T. Daher, R.H. Mohtar, Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making, Water Int. 40 (5–6) (2015) 748–771, https://doi.org/10.1080/02508060.2015.1074148.

[60] J.G. Arnold, D.N. Moriasi, P.W. Gassman, K.C. Abbaspour, M.J. White, R. Srinivasan, M.K. Jha, SWAT: model use, calibration, and validation, Trans. ASABe 55 (4) (2012) 1491–1508, https://doi.org/10.13031/2013.42244.

[61] M. Giampietro, R.J. Aspinall, S.G.F. Bukkens, J.C. Benalcazar, F. Diaz-Maurin, A. Flammini, T. Gomiero, Z. Kovacic, C. Madrid, J. Ramos-Martín, T. Serrano-Tovar, An Innovative Accounting Framework For the Food-Energy-Water nexus: Application of the MuSIASEM Approach to Three Case Studies, FAO, 2013. Environment and Natural Resources Working Paper No. 56.

[62] J.W. Jones, G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, J.T. Ritchie, The DSSAT cropping system model, Eur. J. Agron. 18 (3–4) (2003) 235–265, https://doi.org/10.1016/S1161-0301(02)00107-7.

[63] A.J. Seebregts, G.A. Goldstein, K. Smekens, Energy/environmental modeling with the MARKAL family of models, P. Chamoni, R. Leisten, A. Martin, J. Minnemann, & H. Stadtler (Eds.), in: Operations Research Proceedings 2001 2001, Springer, 2002, pp. 75–82, https://doi.org/10.1007/978-3-642-50282-8_10.

[64] P. Karimi, A.S. Qureshi, R. Bahramloo, D. Molden, Reducing carbon emissions through improved irrigation and groundwater management: a case study from Iran, Agric. Water Manage 108 (2012) 52–60.

[65] A.D. Marta, F. Natali, M. Mancini, R. Ferrise, M. Bindi, S. Orlandini, Energy and water use related to the cultivation of energy crops: a case study in the Tuscany region, Ecol. Soc. 16 (2) (2011).

[66] M. Donatelli, C. Stöckle, E. Ceotto, M. Rinaldi, Evaluation of CropSyst for cropping systems at two locations of northern and southern Italy, Eur. J. Agron. 6 (1–2) (1997) 35–45, https://doi.org/10.1016/S1161-0301(96)02014-8.

[67] E.G. Davies, S.P. Simonovic, ANEMI: a new model for integrated assessment of global change, Interdiscip. Environ. Rev. 11 (2–3) (2010) 127–161, https://doi.org/10.1504/IER.2010.037355.

[68] J. Sieber, D. Purkey, User Guide For Water Evaluation and Planning System (WEAP), Stockholm Environment Institute, 2015.

[69] A. Karnib, A quantitative assessment framework for water, energy, and food nexus, Comput. Water Energy Environ. Eng. 6 (2017) 11–23, https://doi.org/10.4236/cweee.2017.61002.

[70] P.M. Reed, A. Hadjimichael, K. Malek, T. Karimi, C.R. Vernon, V. Srikrishnan, J. S. Rice, Addressing Uncertainty in Multisector Dynamics Research [Book], Zenodo, 2022, https://doi.org/10.5281/zenodo.6110623.

[71] Anandhi, A., Srivastava, P., Mohtar, R., Lawford, R., Sen, S., & Lamba, J. (2022, in press). Methodologies and principles for developing nexus definitions and conceptualizations. Transactions of the ASABE. 10.13031/ja.14539.

[72] C. Fernandes Torres, C. Peixoto de Lima, B. Suzart de Almeida Goodwin, T. Rebello de Aguiar Junior, A. Sousa Fontes, D. Veras Ribeiro, R. Saldanha Xavier da Silva, Y. Dantas Pinto Medeiros, A literature review to propose a systematic procedure to develop "nexus thinking" considering the water–energy–food nexus, Sustainability 11 (2019) 7205, https://doi.org/10.3390/su11247205.

[73] R.H. Mohtar, The WEF Nexus journey, Front. Sustain. Food Syst. (2022), https://doi.org/10.3389/fsufs.2022.820305, 6, 820305.

[74] Conference B.. (2011). The water, energy and food security nexus – Solutions for the green economy: conference synopsis (February 2012).

[75] Mohtar, R., & Daher, B. (2012). Water, energy, and food: the ultimate nexus. In Encyclopedia of Agricultural, Food, and Biological Engineering (2nd ed.). 10.1081/E-EAFE2-120048376.

[76] United Nations Educational, Scientific and Cultural Organization (UNESCO). (2021). Implementing the water–Energy–Food–Ecosystems nexus and achieving the Sustainable Development Goals (C. Carmona-Moreno, E. Crestaz, Y. Cimmarrusti, F. Farinosi, M. Biedler, A. Amani, A. Mishra, & A. Carmona-Gutierrez, Eds.).

[77] Allouche, J., Middleton, C., & Gyawali, D. (2014). Nexus nirvana or nexus nullity? A dynamic approach to security and sustainability in the water–energy–food nexus (STEPS Working Paper 63). STEPS Centre.

[78] R.C. De Loë, J.J. Patterson, Rethinking water governance: moving beyond water-centric perspectives in a connected and changing world, Nat. Resour. J. 57 (1) (2017) 75–100.

[79] Keulertz, M., Sowers, J., Woertz, E., & Mohtar, R. (2016). The water-energy-food nexus in arid regions: the politics of problem sheds. In K. Conca & E. Weinthal (Eds.), The Oxford Handbook of Water Politics and Policyhttps:10.1093/oxfordhb/9780199335084.013.28.

[80] D. Waughray, Water Security: The Water-Food-Energy-Climate Nexus, Island Press and the World Economic Forum, 2011. http://www3.WEForum.org/docs/WEF_WI_WaterSecurity_WaterFoodEnergyClimateNexus_2011.pdf.

[81] G. Boccaletti, Charting Our Water Future, McKinsey, 2009.

[82] FAO, Technical workshop: Moving ahead to Implement the Nexus approach: Lessons learned and Discussion of Next Steps Regarding Integrated Assessment of Water-Energy-Food Needs in a Climate Change Context, FAO, Rome, 2013 b. http://www.fao.org/energy/36642-025df158829c7a38e35b6ce87337bdbca.pdf.

[83] World Bank, World Bank Supports Morocco's bold Solar Power Plans, World Bank, 2011.

[84] R.H. Mohtar, A call for a new business model valuing water use and production: the water, energy and food nexus holistic system approach, Water Int. 42 (6) (2017) 773–776, https://doi.org/10.1080/02508060.2017.1353238.

[85] Sivaram, V., Norris, T., McCormick, C., & Hart, D.M. (2016). Energy innovation policy: Priorities for the Trump administration and Congress. Information Technology & Innovation Foundation.

[86] R.H. Mohtar, R. Lawford, Present and future of the water-energy-food nexus and the role of the community of practice, J. Environ. Stud. Sci. 6 (1) (2016) 192–199, https://doi.org/10.1007/s13412-016-0378-5.

[87] Nexus S.F.W.E.. (2017). Sustainable Urbanization Global Initiative Food-Water-Energy Nexus: Joint call for proposals.

[88] E. Martinez-Hernandez, M. Leach, A. Yang, Understanding water-energy-food-ecosystem interactions using the nexus simulation tool NexSym, Appl. Energy (2017), https://doi.org/10.1016/j.apenergy.2017.09.022, 206.

[89] International Water Resources Association (IWRA). (2017). Policy briefing: sustainability in the water-energy-food nexus. Retrieved from http://www.iwra.org.

[90] C.F.T. Paez, O.V. Salazar, The Water-Energy-Food Nexus: an analysis of food sustainability in Ecuador, Resources (2022), https://doi.org/10.3390/resources11100090.

[91] Mediterra, Zero Waste in the Mediterranean: Natural resources, Food and Knowledge, CIHEAM & FAO, 2016.

[92] SAWM. (2016). Support to agricultural water management in the Horn of Africa through the Partnership for Agricultural Water in Africa (AgWA): terminal report.

[93] O.W. Johnson, L. Karlberg, Co-exploring the water-energy-food nexus: facilitating dialogue through participatory scenario building, Front. Environ. Sci. 5 (2017) 24, https://doi.org/10.3389/fenvs.2017.00024.

[94] A.R. Dariah, A.Y. Mafruhat, E. Hendrakusumah, Framework of sustainable development planning in Indonesia, Jo. Phys. Conf. Ser. 1375 (1) (2019) 012028, https://doi.org/10.1088/1742-6596/1375/1/012028. IOP Publishing.

[95] United Nations. (2016 a). Developing the capacity of ESCWA member countries to address the water and energy nexus for achieving Sustainable Development Goals: regional policy toolkit.

[96] De Petrillo, E., Falsetti, B., Sciarra, C., & Tuninetti, M. (2021). Water to food: a data-viz book about the water footprint of food production and trade. https://hdl.handle.net/11583/2978858.

[97] S. Fabiani, S. Vanino, R. Napoli, P. Nino, Water-energy-food nexus approach for sustainability assessment at farm level: an experience from an intensive agricultural area in central Italy, Environ. Sci. Policy 104 (2020) 1–12.

[98] L. Mateos, A.C. dos Santos Almeida, J.A. Frizzone, S.C.R.V Lima, Performance assessment of smallholder irrigation based on an energy-water-yield nexus approach, Agric. Water Manage 206 (2018) 176–186.

[99] S.H. Sadeghi, E.S. Moghadam, M. Delavar, M. Zarghami, Application of water-energy-food nexus approach for designating optimal agricultural management pattern at a watershed scale, Agric. Water Manage 233 (2020) 106071.

[100] J.L. Hatfield, T.J. Sauer, R.M. Cruse, Soil: the forgotten piece of the water, food, energy nexus, Adv. Agron. 143 (2017) 1–46.

[101] R. Lal, R.H. Mohtar, A.T. Assi, R. Ray, H. Baybil, M. Jahn, Soil as a basic nexus tool: soils at the center of the food-energy-water nexus, Curr. Sustain./Renew. Energy Rep. 4 (3) (2017) 117–129.

[102] M.H. Saray, A. Baubekova, A. Gohari, S.S. Eslamian, B. Klove, A.T. Haghighi, Optimization of water-energy-food nexus considering CO2 emissions from cropland: a case study in northwest Iran, Appl. Energy 307 (2022) 118236.

[103] P.R. Yoon, S.H. Lee, J.Y. Choi, S.H. Yoo, S.O. Hur, Analysis of climate change impact on resource intensity and carbon emissions in protected farming systems using Water-energy-food-carbon Nexus, Resour. Conserv. Recycl. 184 (2022) 106394.

[104] I. Nuwayhid, R.H. Mohtar, The water, energy, and food nexus: health is yet another resource, Front. Environ. Sci. 10 (2023) 879081, https://doi.org/10.3389/fenvs.2022.879081.

[105] J.D. Muell, R.H. Mohtar, E.S. Kan, A.T. Assi, V. Pappa, Farm scale water-energy-food-waste nexus analysis for a closed loop dairy system, Front. Environ. Sci. 10 (2022) 880839, https://doi.org/10.3389/fenvs.2022.880839.

[106] L. Van den Heuvel, M. Blicharska, S. Masia, J. Sušnik, C. Teutschbein, Ecosystem services in the Swedish water-energy-food-land-climate nexus: anthropogenic pressures and physical interactions, Ecosyst. Serv. 44 (2020) 101141.

[107] B. Daher, S. Hamie, K. Pappas, J. Roth, Examining Lebanon's resilience through a water-energy-food nexus lens, Front. Sustain. Food Syst. 6 (2022) 748343, https://doi.org/10.3389/fsufs.2022.748343.

[108] A.E. Ioannou, C.S. Laspidou, Resilience analysis framework for a water–energy–food nexus system under climate change, Front. Environ. Sci. 10 (2022) 820125, https://doi.org/10.3389/fenvs.2022.820125.

[109] X. Wang, P. Jiang, L. Yang, Y.V. Fan, J.J. Klemeš, Y. Wang, Extended water-energy nexus contribution to environmentally related Sustainable Development Goals, Renew. Sustain. Energy Rev. 150 (2021), https://doi.org/10.1016/j.rser.2021.111485.

[110] S.H. Lee, A.T. Assi, R.H. Mohtar, M. Hamane, P.R. Yoon, S.H. Yoo, Development of WEF-P nexus based on product-supply chain: a case study of phosphorous fertilizer industry in Morocco, Sci. Total Environ. 857 (2023) 159520.

[111] H. Hussein, F. Ezbakhe, The Water–Employment–Migration nexus: buzzword or useful framework? Dev. Policy Rev. 00 (2023) e12676, https://doi.org/10.1111/dpr.12676.

[112] B. Suárez-Eiroa, E. Fernández, G. Méndez-Martínez, D. Soto-Oñate, Operational principles of circular economy for sustainable development: linking theory and practice, J. Clean. Prod. 214 (2019) 952–961.

[113] World Economic Forum. (2019). Global risks 2019 (14th ed.). http://www3.weforum.org/docs/WEF_Global_Risks_Report_2019.pdf.

[114] I.nternational Renewable Energy Agency (IRENA). (2015). Renewable energy in the water, energy & food nexus.

[115] Lee, B., Preston, F., Kooroshy, J., Bailey, R., & Lahn, G. (Eds.). (2012). Resources futures. Royal Institute of International Affairs.

[116] R.A. Matthew, J. Barnett, B. McDonald, K.L. O'Brien, Global Environmental Change and Human Security, MIT Press, 2010.

[117] Maas, A., Issayeva, G., Rüttinger, L., Umirbekov, A., & Daussa, R. (2012). Climate change and the water-energy-agriculture nexus in Central Asia. adelphi.

[118] R. Mohtar, Opportunities in the water-energy-food nexus approach: innovatively driving economic development, social wellbeing, and environmental sustainability, Sci. Total Environ. (2018).

[119] B. Daher, R.H. Mohtar, E.N. Pistikopoulos, K.E. Portney, R. Kaiser, W. Saad, Developing socio-techno-economic-political (STEP) solutions for addressing resource nexus hotspots, Sustainability 10 (2) (2018) 512, https://doi.org/10.3390/su10020512.

[120] C. Pahl-Wostl, An evolutionary perspective on water governance: from understanding to transformation, Water Resourc. Manag. 31 (10) (2017) 2917–2932, https://doi.org/10.1007/s11269-017-1727-1.

[121] K.E. Portney, A. Vedlitz, G. Sansom, P. Berke, B.T. Daher, Governance of the water-energy-food nexus: the conceptual and methodological foundations for the San Antonio region case study, Curr. Sustain./Renew. Energy Rep. 4 (3) (2017) 160–167.

[122] F. Artioli, M. Acuto, J. McArthur, The water-energy-food nexus: an integration agenda and implications for urban governance, Polit. Geogr. 61 (2017) 215–223, https://doi.org/10.1016/j.polgeo.2017.08.009.

[123] D. Benson, A.K. Gain, J. Rouillard, C. Giupponi, Governing for the nexus, P. A Salam, S. Shrestha, V. P. Pandey, & A. K. Anal (Eds.). Water-Energy-Food Nexus: Principles and Practices, John Wiley & Sons, 2017, pp. 77–88.

[124] B. Daher, S.H. Lee, V. Kaushik, J. Blake, M.H. Askariyeh, H. Shafiezadeh, S. Zamaripa, R.H. Mohtar, Towards bridging the water gap in Texas: a water-energy-food nexus approach, Sci. Total Environ. 647 (2019) 449–463, https://doi.org/10.1016/j.scitotenv.2018.07.297.

[125] O.O. Ololade, S. Esterhuyse, A.D. Levine, The water-energy-food nexus from a South African perspective, P. A Salam, S. Shrestha, V. P Pandey, & A. K. Anal (Eds.). Water-Energy-Food Nexus: Principles and Practices, John Wiley & Sons, Inc, 2017.

[126] B. Schreiner, H. Baleta, Broadening the lens: a regional perspective on water, food, and energy integration in SADC, Aquat. Procedia 5 (2015) 90–103, https://doi.org/10.1016/j.aqpro.2015.10.011.

[127] B. Daher, W. Saad, S.A. Pierce, S. Hülsmann, R.H. Mohtar, Trade-offs and decision support tools for FEW nexus-oriented management, Curr. Sustain. Renew. Energy Rep. 4 (3) (2017) 153–159, https://doi.org/10.1007/s40518-017-0081-0.

[128] C. Stein, L.J. Jaspersen, A relational framework for investigating nexus governance, Geogr. J. 185 (4) (2019) 377–390, https://doi.org/10.1111/geoj.12345.

[129] A. Stirling, Developing 'Nexus Capabilities': Towards Transdisciplinary Methodologies (Version 1), University of Sussex, 2015. https://hdl.handle.net/10779/uos.23446508.v1.

[130] N. Weitz, C. Strambo, E. Kemp-Benedict, M. Nilsson, Closing the governance gaps in the water-energy-food nexus: insights from integrative governance, Glob. Environ. Change 45 (2017) 165–173, https://doi.org/10.1016/j.gloenvcha.2017.06.006.

[131] R.M. Stephan, R.H. Mohtar, B. Daher, A. Embid Irujo, A. Hillers, J.C. Ganter, L. Karlberg, L. Martin, S. Nairizi, D.J. Rodriguez, W. Sarni, Water–energy–food nexus: a platform for implementing the Sustainable Development Goals, Water Int. 43 (3) (2018) 472–479, https://doi.org/10.1080/02508060.2018.1446581.

[132] M. Al-Saidi, H. Hussein, The water-energy-food nexus and COVID-19: towards a systematization of impacts and responses, Sci. Total Environ. 779 (2021) 146529, https://doi.org/10.1016/j.scitotenv.2021.146529.

[133] M. Al-Saidi, S. Saliba, Water, energy, and food supply security in the gulf cooperation council (GCC) countries—a risk perspective, Water 11 (3) (2019) 455, https://doi.org/10.3390/w11030455 (Basel).

[134] COP22. (2016). Outcome document of the action event on water. Marrakesh, 2016.

[135] United Nations - Water, Water Security and the Global Water Agenda, UN-Water Analytical Brief). United Nations University, 2013.

[136] S. Kuzma, M.F.P. Bierkens, S. Lakshman, T. Luo, L. Saccoccia, E.H. Sutanudjaja, R. Van Beek, Aqueduct 4.0: Updated decision-Relevant Global Water Risk Indicators [Technical Note], World Resource Institute, 2023, https://doi.org/10.46830/writn.23.00061.

[137] Economist Impact, The Global Food Security Index 2022, The Economist Group, 2022.

[138] A. Azzuni, C. Breyer, Global energy security index and its application on national level, Energies 13 (10) (2020) 2502, https://doi.org/10.3390/en13102502 (Basel).

[139] U.S. Chamber of Commerce's Global Energy Institute. (2020). International index of energy security risk report. Global Energy Institute. https://www.uschamber.com/assets/documents/gei/IESRI-Report_2020_4_20_20.pdf.

[140] H.O. Pörtner, D. Roberts, E. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, A. Okem, Technical summary: climate Change 2022: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge University Press, 2022.